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West Virginia
University

FINAL REPORT

U. S. Bureau of Mines Grant G0155011
U. S. Energy Research and Development Administration
Contract E-(46-1)-8040
U. S. Department of Energy Contract EY-76-S-21-8040

Robert C. Shumaker, Project Director

Title: Application of Remote Sensing Studies to the Interpretation of Fracture Systems and Structural Styles in the Plateau Regions of Eastern Kentucky, Southwestern Virginia, and Southwestern West Virginia for Application to Fossil Fuel Extraction Processes.

Author: Eberhard Werner

Date: December 1977

Prepared for the Department of Energy

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APPLICATION OF REMOTE SENSING STUDIES TO THE INTERPRETATION OF FRACTURE SYSTEMS AND STRUCTURAL STYLES IN THE PLATEAU REGIONS OF EASTERN KENTUCKY, SOUTHWESTERN VIRGINIA, AND SOUTHWESTERN WEST VIRGINIA FOR APPLICATION TO FOSSIL FUEL EXTRACTION PROCESSES

Eberhard Werner

FINAL REPORT

CONTRACT NO. EY-76-S-21-8040

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SUMMARY AND RECOMMENDATIONS

A. Investigation of photolineament mapping techniques has shown:

1. Photolineament mapping techniques must be consistent if comparable work is to be done by different operators and/or in different areas. Considerable further work is still to be done to determine the causes of inter-operator variation in mapping.
2. Image variations are responsible for significant differences in the resulting photolineament maps. Factors in decreasing order of importance are image scale, image contrast, and image density.
3. Even when variables introduced by inter-operator variation and image quality are minimized, there is very little coincidence of photolineament position on maps obtained from different source images. Distributions of photolineament orientation and length, on the other hand, will not vary significantly for the same map pair. Clearly, much work needs to be done to develop methods which provide much greater positional coincidence for photolineament map pairs produced from different images and/or by different operators.
4. Although the method is not directly applicable in the areas of the western Appalachian Plateau investigated in this project, for those areas where photolineament maps can be used to plan well drilling sites, a sucession of maps at ever-enlarging scales should be used to select favorable sites.

B. Relationships exist between photolineaments and bedrock geology in the Appalachian Basin:

1. Prominent photolineament orientations appear at N 75°E, N12°W, N 40°E, N 55°W, and N 70°W on regional maps. N 55°W and N 70°W are directions

perpendicular to the strike of the Southern and Central Appalachians, respectively. The other directions may be related to older basement structures.

2. Folds and faults in the Paleozoic rocks commonly change direction or intensity, or terminate near prominent very long photolineaments.
3. A high density of photolineaments appears to delineate the 38th Parallel Lineament zone in West Virginia.
4. Singly photolineaments and prominent fracture directions in outcrops on or near the photolineament tend to be parallel. This relationship tends to be lost if the data is averaged for large areas.

C. Investigation of the relationship between natural gas production and photolineament position in the Appalachian Basin has shown:

1. The relationship is extremely complex, and may be overshadowed by other variables such as stratigraphy, structure, and lithology.
2. Exceptionally high natural open flows in Jackson, Mason, and Wayne counties are found away from photolineaments rather than on them.
3. High stimulated open flows are apparently distributed without regard to photolineament location as determined within the limitations of the data available. Since the test areas for this project were outside of the area of the Appalachian tectonic allochthon, further work of this nature should be done within that area.

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Chapter 1 INTRODUCTION

Section 1 Project Background

Much of the world's mineral wealth is produced from natural rock fractures. For example, many of the low-temperature hydrothermal mineral deposits--primarily lead, zinc, and copper--are in crevices in natural fracture systems. Often these deposits are concentrated where fracture permeability has allowed water to dissolve away some of the parent rock. Subsequently, the fractures became avenues of permeability which allowed mineral bearing fluids to migrate and collect.

Not all mineral resources are solid. Fluids of various types are of at least equal, if not greater importance than the solids. Ground water has been produced from relatively impermeable rocks for many years by prospecting for fractures and fracture zones. Water, of course, is not the only fluid produced. Hydrocarbons--oil and gas--are often found in fractured reservoirs where the fractures provide both the migration paths and the reservoir space. Oil is produced from fractures in the shales of the Niobrara Formation of Colorado and Wyoming (Harnett, 1968). Hydrocarbons are derived from fractures in the shales of the Permian Basin of West Texas.

Of considerable interest at the present time is the large reserve of natural gas held in the Devonian shales of the Appalachian Basin. It has been estimated that 460 quadrillion cubic feet--potentially 200 to 300 years supply--is contained in these rocks. Under present or near future conditions of economics and technology, about 285 trillion cubic feet could be produced, mainly from fractures (Brooks, 1972). However, the low yield rate of these gas wells makes them of only marginal operability. If some means could be found to increase the average yield rate of these wells, a larger proportion of gas might be extractable.

Generally, natural rock fractures are not positioned at random, nor do they lie in random directions. Numerous studies which have been made of such natural fractures indicate that they are normally developed in well-defined systems with preferred orientations reflecting the region's stress history. A knowledge of such fracture systems, both for specific localities as well as for an entire region, can be of considerable aid in interpreting the history of the area. Such an interpretation can be of considerable use in the mapping of residual stress fields which are important for predicting preferred permeability directions and orientation of open natural fractures as well as directions of induced fractures during well stimulation operations.

Natural fracture systems can be mapped by a number of methods of varying reliability and cost. Direct field methods using borings and high resolution seismic or resistivity surveys are reliable but very expensive. Field measurement of surface fractures to predict subsurface fractures can be quite reliable and somewhat less expensive, but is useful only in terra where outcrops of rock are plentiful.

An indirect method which has been proven reliable in some areas is to map photolineaments. The orientations of these photolineaments are related to the orientation of surface and subsurface fractures and to residual stress fields. Also, the locations of the photolineaments are locations of zones of natural fractures. However, the method has been tested only in a few areas and, even then, it is still unknown whether the method will work under various conditions related to both the individuals doing the work and the imagery being used.

The present project was conceived in order to test this remote sensing method in what was thought to be a somewhat more difficult area than those to which remote sensing methods have been previously applied. Previous applications of photolineament mapping to delineating natural fracture zones have generally been in areas of sparse vegetation or thin soils, or where pronounced geological structures are fairly close to the surface.

Section 2 Geography and Geology of the Project Area

During the project various portions of the area shown in figure 1 were investigated. Most phases of this study involved only small portions of the overall area and will be shown individually in the discussion. The overall area encompasses southern and western West Virginia, eastern Kentucky, and small adjacent portions of Virginia and Ohio.

There are several reasons--both geographical and geological--for choosing this area:

1. Already mentioned above, remote sensing methods in mineral exploration, and particularly methods employing photolineament mapping, have been used successfully in terrains which were either arid or of low relief or both. The Appalachian Plateau area is both rugged topographically and has almost complete vegetative cover. As a result, very little direct observation of the ground surface and particularly of the rocks can be done from aerial imagery.
2. Previous studies were mainly in areas of strong, prominent geological structures. Although there are pronounced structures at or near the surface in the Valley and Ridge province (see figure 2), most of the area either has very subdued structures or else they are so deeply buried as to be nearly indetectable at the surface. To investigate photolineament patterns over these deeply buried structures was one of the intentions of this project. Note the differences in strength of

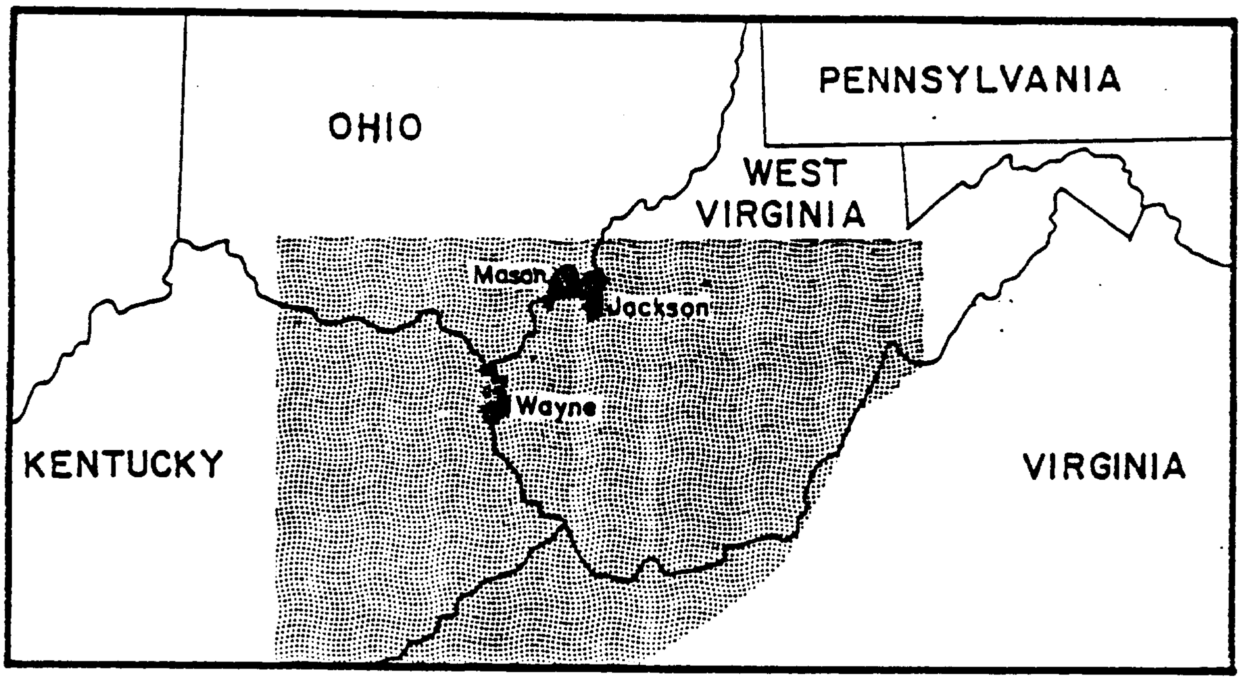

Figure 1. Location of project area. Stippled area is overall general study area. Jackson, Mason, and Wayne counties, West Virginia, were used in the investigation of gas production.

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Figure 2. Landsat image of the area indicated in figure 1. Image has been photographically enhanced from the mosaic produced by the Soil Conservation Service, U. S. Department of Agriculture.

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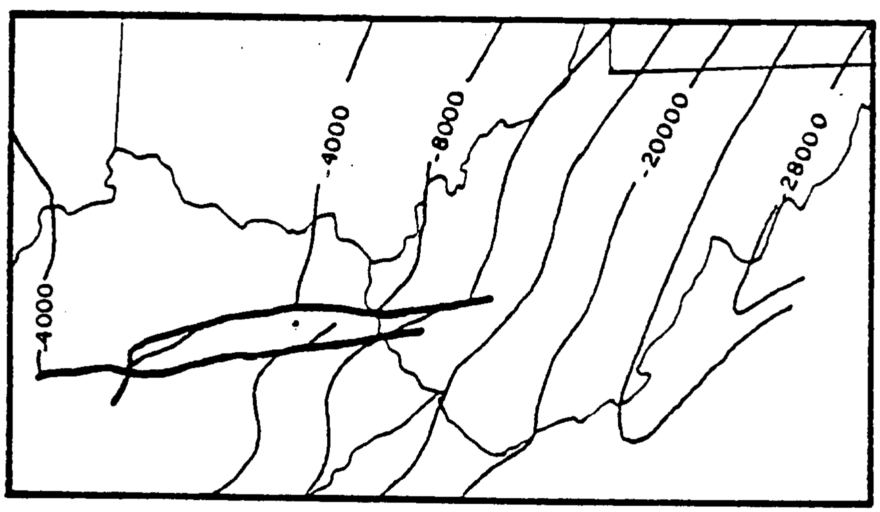

Figure 3. Basement structure of the study area. Contours on basement indicate a slope to the east from the Cincinnati Arch. Heavy lines are basement faults. Contour interval is 4000 feet (after Tectonic Map of North America, 1961).

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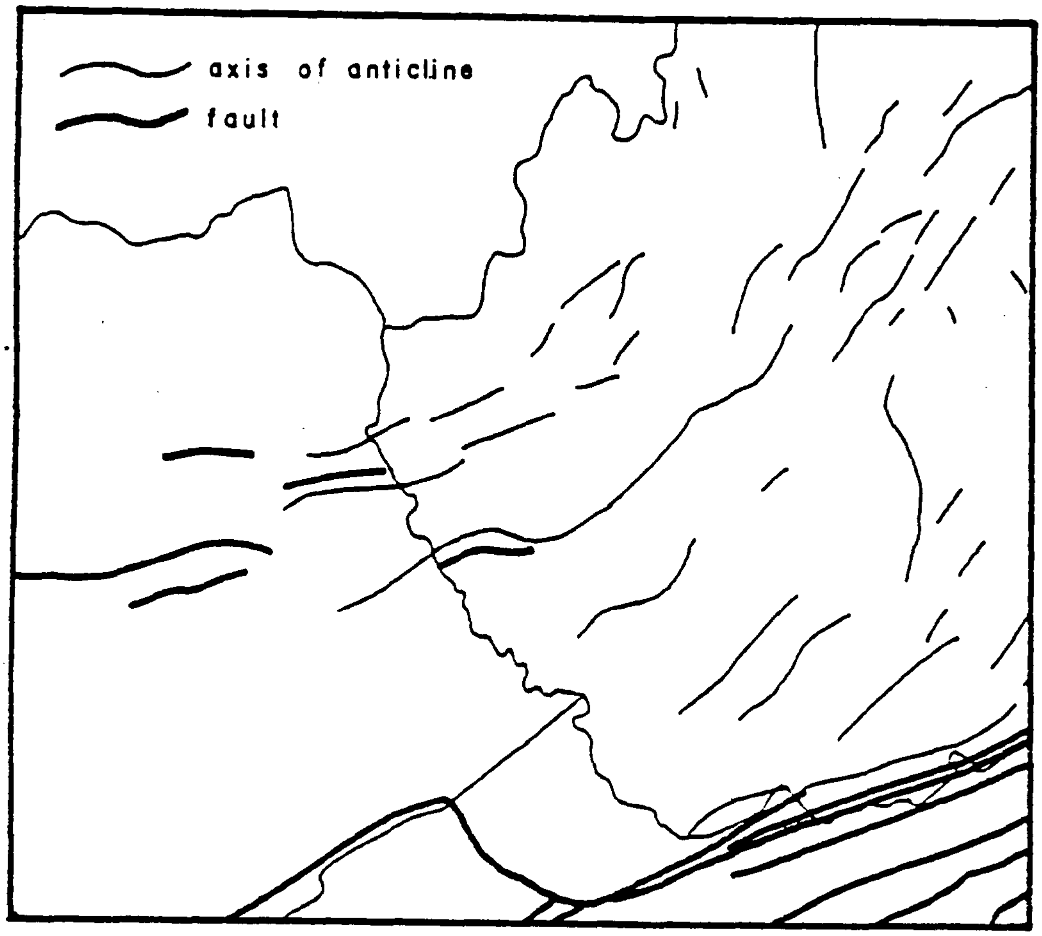

Figure 4. Structures of the surface rocks of eastern Kentucky and southern West Virginia (after Woodward, 1968).

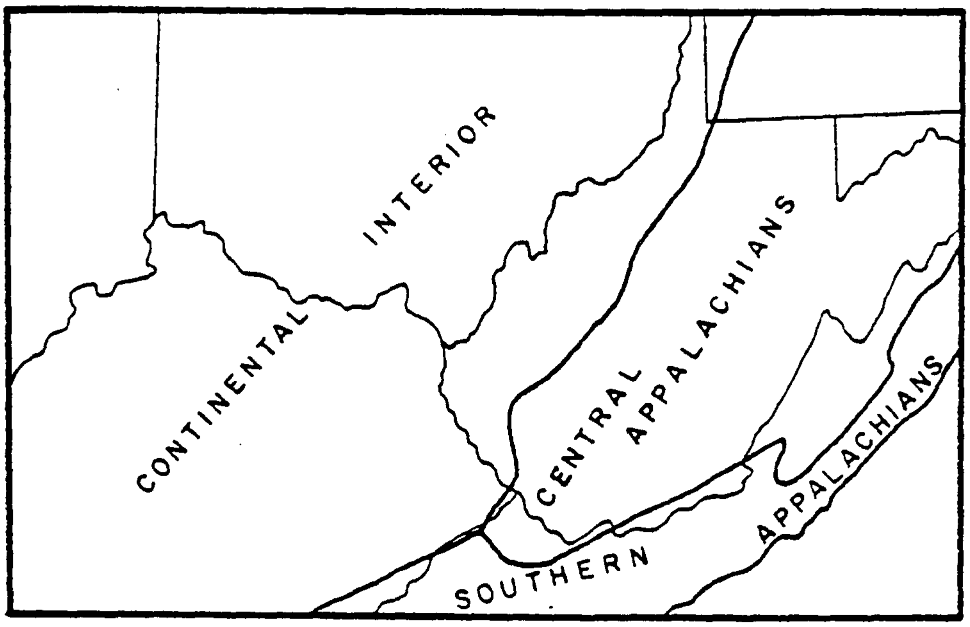

Figure 5. Tectonic provinces of the study area (modified from Hadley and Devine, 1974).

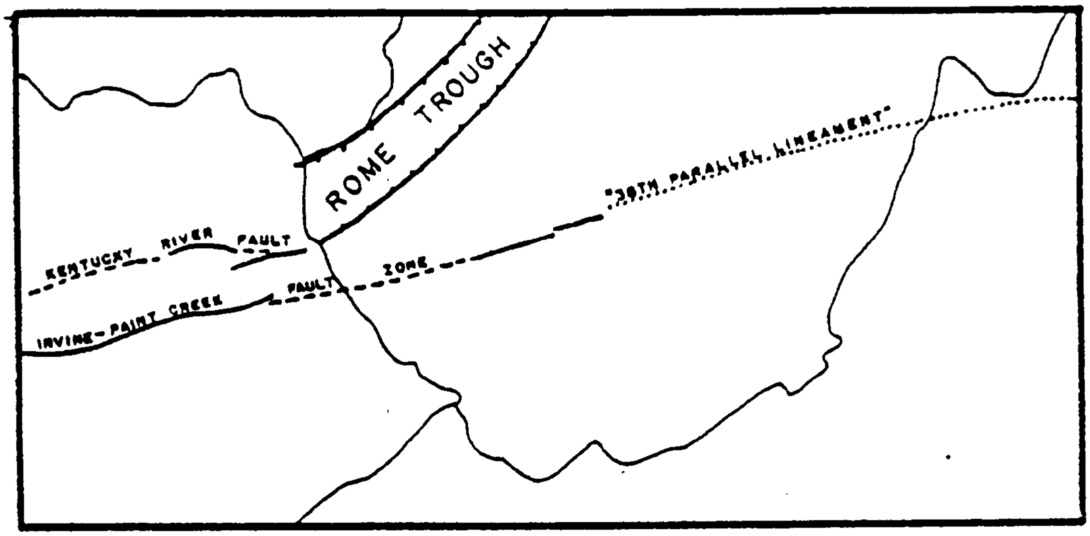

Figure 6. Location of Kentucky River and Irvine-Paint Creek fault zones and West Virginia extension of 38th Parallel Lineament (after Heyl, 1972), and Rome Trough.

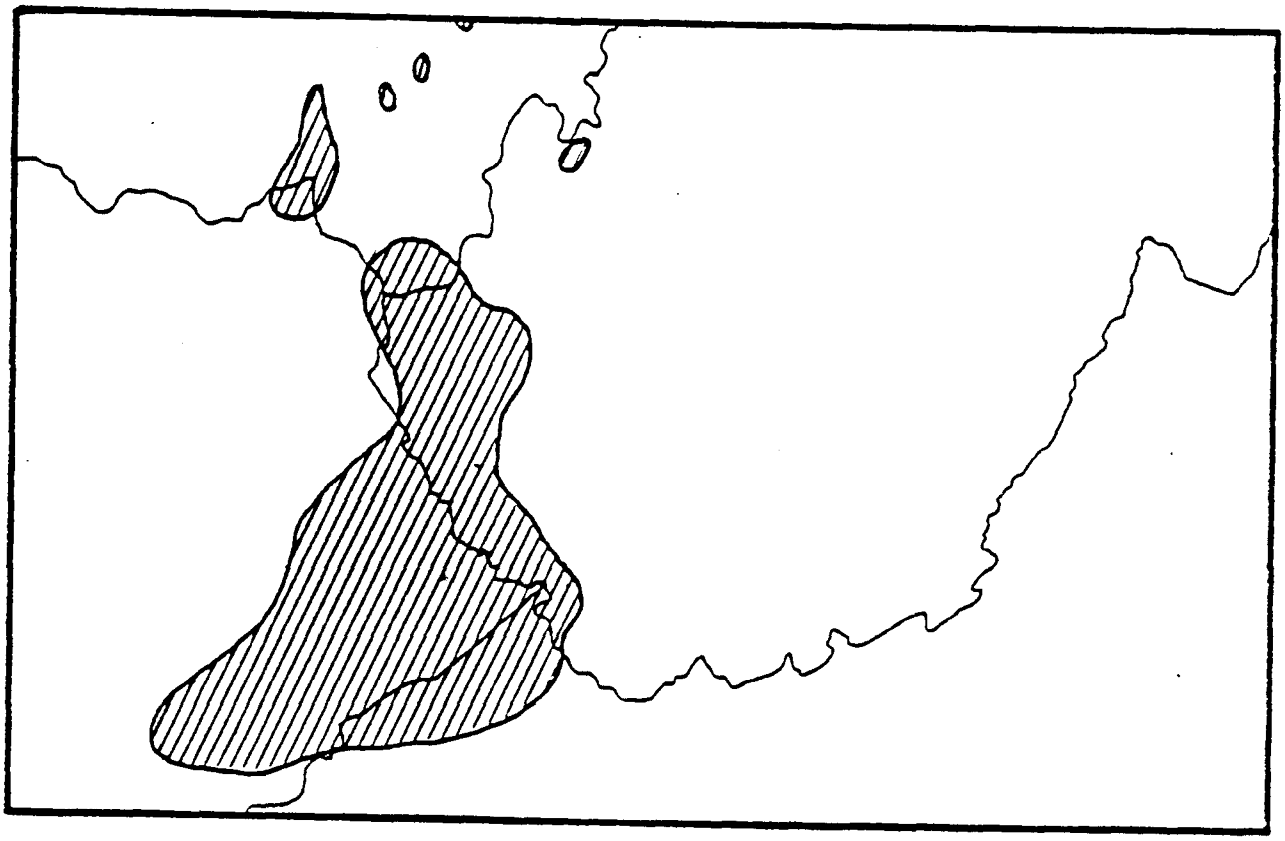

Figure 7. Areas of gas production from the Devonian shales are shown as lined areas (modified from deWitt, Perry, and Wallace, 1975).

7. Various types of remote sensing imagery are available for the area or portions thereof. This includes not only conventional black-and-white mapping photography, but also color-infrared photography, Skylab and Landsat satellite images, and some side-locking radar and thermal infrared. A catalog of all imagery for West Virginia was recently released (Woodring, 1977). Such variety of imagery allows for the comparison of the effectiveness of the various types for various purposes as well as evaluation of the mapping methods used.

Section 3 Some Basic Definitions

One problem which arose early during this study was one of terminology. There are numerous cases in the published literature in which the same term may be used with several meanings or several terms used for the same feature. The terms under discussion for this project are joint, fault, fracture, lineament, fracture trace, lineation, and linear.

Joint and fracture are often used interchangeably in the literature. Dennis (1967) used the definition of joint originally published by Leith (1923): Rock fracture or fissure along which there has been little or no movement. This is intended to contrast with fault, that is, a fracture along which there has been discernable movement. Since the criteria for movement depend partly on the scale of the investigation and since the unmodified term joint normally implies the systematic joints, the word fracture is used throughout this study for both systematic and nonsystematic joints as well as faults with minor movement. It was felt that such fractures as were found in the field study could not be subdivided into the above groups in most cases. Thus, in the field outcrop work, any broken rock surface not obviously artificially created was given equal consideration.

Probably no group of terms has been more misused in the recent geological literature than the terms linear, lineation, fracture trace, and lineament. All have been applied to those linear features seen on imagery. Although the term linear has been used as a noun in several reports in recent years, such usage is grammatically incorrect. Therefore, this term will only be used as an adjective in this report. More, however, will be said about this term below.

"Lineation includes all linear structures in rocks without regard to origin (after E. Cloos, 1946, p. 1). The term excludes purely superficial features, such as glacial striation" (Dennis, 1967). In general, this definition implies that lineation refers to rock fabric characteristics. Common usage has somewhat extended the scope of the term but even then it refers to features which may be expression in terms of an orientation but not of a position. For example, Fairbarn (1949, p. 5) defines lineation as "parallelism of linear elements." Such a definition obviously eliminates the concept of position of a lineation.

The remaining two terms, fracture trace and lineament, refer to single, linear features. Lineament has been variously defined. Dennis (1967, p. 102) defines it as a "rectilinear or gently curved alignment of topographic features on a regional scale, generally judged to reflect crustal structure, ...'Lineament' most often refers to regional structures..."

Earlier usage of the term is generally quite similar. Hobbs (1904) defines the term as "nothing more than a generally rectilinear earth feature." It could be "(1) crests of ridges or the boundaries of elevated areas, (2) drainage lines, (3) coast lines, and (4) boundary lines of geologic formations, of petrographic rock types, or of lines of outcrops." Kelley (1955) defines lineament as "...a rectilinear feature of considerable extent on the surface of the earth." An unfortunate variation was introduced by Sonder (1938) in that he proposed "that the concept 'lineament' be used as a general designation. The lineament of a region then denotes a definite direction which is contained in the tectonics, the jointing and the relief." This definition has many similarities to the definition of lineation. Sonder's concept might be termed tectonic lineation in that this would describe direction but not position of essentially a group of parallel linear structures. Fortunately, Sonder's variant on the definition of lineament does not appear to have been widely used in the English-language literature.

Dennis (1967) has restricted lineament to alignments of topographic features. Present usage, however, indicates that this definition is too restrictive. Lineament today refers to virtually any type of alignment of features on maps and photographs or in the field. Gwinn (1964) drew a number of map lines which he called lineaments. These were based on subsurface structural information, not topography. Rodgers (1970) drew lineaments by connecting ends of structural axes on a geologic map. Gay (1972) used the term for linear features on aeromagnetic maps. Heyl (1972) applied the name 38th Parallel Lineament to an alignment of mapped geologic features. Thus it appears that it is now best to modify the term whenever it is used. Therefore, Dennis' lineaments are topographic lineaments; Gwinn's and Rodgers' lineaments are structural lineaments; Gay's lineaments are aeromagnetic lineaments; and Heyl's lineament is a geologic lineament.

Most lineament maps produced at present are derived from various forms of aerial imagery - mostly photographs, but also imagery from remote sensing scanners operating outside the visible light band. Wilson (1941) recognized that "large structural features can be better seen in photographs than on the ground. They are not easily confused with anything else, and they show through a moderate cover of drift. Some of these are the great scarps and troughs which cross all the Precambrian rocks in straight or gently curving lines and are termed lineaments or 'breaks'". Kaiser (1950) notes that "a lineament is a straight linear feature that is at least many hundreds of feet and commonly many miles long. Lineaments are well shown on aerial photographs and may consist of (1) linear topographic features, either trenches or ridges; (2) linear vegetation patterns; or (3) linear patterns of soil color or texture." Lattman (1958) investigated photointerpretation techniques involved in mapping lineaments and developed definitions more specific to these techniques. He defines photogeologic lineament as "a natural linear feature consisting of topographic (including straight stream segments), vegetation, or soil tonal alignments, visible primarily on aerial photographs or mosaic , and expressed continuously of discontinuously for many miles." He placed several restrictions of these lines: "Only natural linear features not obviously related to outcrop pattern of tilted beds, lineation and foliation, and stratigraphic contacts are classified as [lineaments]." Problems which were not apparent when the definition was formulated have arisen with the present use of very high altitude and satellite imagery. At these scales it is frequently very difficult or impossible to determine whether or not the restrictions are met. For this reason, it was proposed that the term photolineament be used for all cases of lineaments drawn on the basis of imagery and to use an appropriate modifier if and when the actual nature of the lineament could be ascertained.

Fracture trace is a term related to lineament which was introduced by Lattman (1958) to distinguish between short and long features on aerial photographs. "A photogeologic fracture trace is. . .expressed continuously for less than one mile . . .included in this term are joints mapped on aerial photographs where bare rock is observed." A similar definition to this has been given for linear (see above). Hoppin (1974) feels that linea should be applied to single lines on photographs. Thus, basically linear and fracture trace are approximately equivalent in their use. However, fracture trace has unfortunate genetic conotations. In many cases, such features truly are traces of fractures in the rocks. However, such an assumption should not be made in all cases. Perhaps, the term should be replaced by short photolineament or something similar which has no genetic implication.

In summary, lineament as used in this report is either a continuous linear or curvilinear feature or an alignment of discrete features and short segments of lines. There is no genetic implication in the word, and modifiers should be used to indicate source of the lineament or type of features found along it. Therefore, all features mapped from images of various types are imagery lineaments or photolineaments. The latter is used here because of its simpler form even though it may not be as etymologically accurate as the former.

The above definition of photolineament was developed in a previous paper (Werner, 1976a). Subsequently, O'leary, Friedman, and Poha (1976) have published an additional discussion of the terms related to lineament. Although their definition on the whole agrees with the above definitions, there are some few but important differences. Where these differences exist, the usage in this report is of the earlier report (Werner, 1976a).

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Chapter 2 PHOTOLINEAMENTS AND FRACTURE SYSTEMS

Section 1 Photolineament Mapping

Since the project was based primarily on remote sensing techniques, and, in particular, photolineament mapping, considerable effort was expended to investigate these techniques. A small area (Figures 8 and 9) was chosen which contained portions of all the various topographic types to be expected.

The three types of topographic expression found can be seen in figure 9. At the eastern edge is a terrain of long, narrow ridges of the Appalachian folded belt. To the west in the southern part is an area of coarse-grained topography of the Appalachian Plateau type. West of this is the more typical Appalachian Plateau type of fine-grained topography. As these topographic types are quite different appearing on the imagery, it was thought that this difference might play a part in the mapping. Thus the area of figure 9 (location shown on figure 8), at the junction of the three topographic types, was used for a more intensive investigation of image variables. This is the area on which most of the following is based.

Materials and Techniques

Numerous choices of imagery were available for the study area. Obtained for evaluation were Skylab (summer) and Landsat (summer, fall and winter) imagery, high-altitude color infrared and low-altitude black-and-white photography, and side-looking radar imagery. Using ordinary photographic copying and darkroom techniques, prints were produced at up to 4 scales, 3 contrasts, and 3 densities. With this variety, there exists a potential of 36 different prints of any single original image and up to 20 different original images for any single area, for a total of 720 varieties of prints for a specific area. There were never this many prints, and hence maps, made; in fact, the maximum number of maps produced for any area was about 25, made from

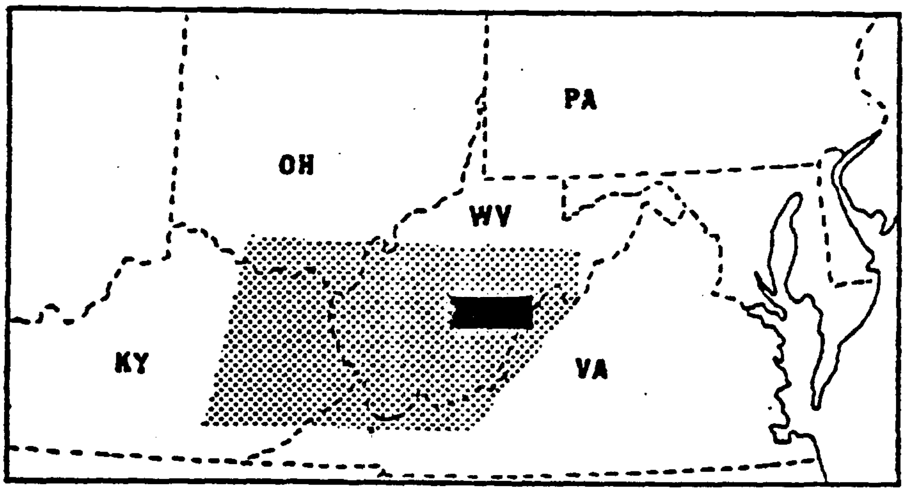

Figure 8. Location of area used for the photolineament mapping test case.

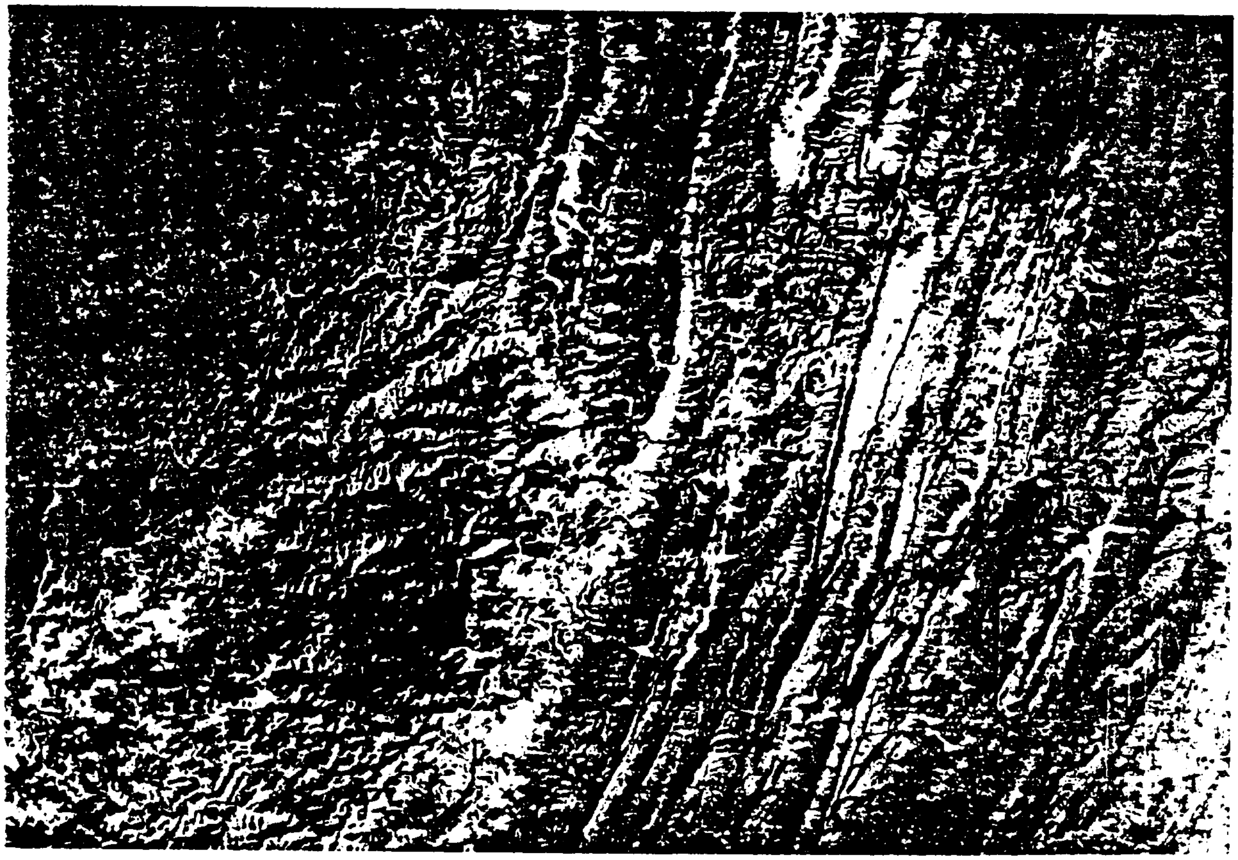

Figure 9. Landsat image of the area used for the photolineament mapping test case (NASA image ERTS E-1172-15310, 11 January 1973).

somewhat fewer images.

Because of the plan to use only low-cost procedures and because only visual interpretation has proved effective in the type of terrain here considered, the mapping techniques are largely based on those recommended by Lattman (1958) with departures only because he did not consider anything but aircraft photography. Mapping was normally done with colored pencils directly on the photographic prints, although occasional clear and frosted overlays were used. Two different viewing methods may be used during mapping: 1) close inspection of the image from close by and perpendicularly above it (that is, the "normal" viewing method), and 2) viewing from a low angle or a considerable distance. The maps produced are quite different; the type 1 map consists of more, shorter lineaments than the type 2 map. Which map is made will depend on the purpose to which it will be put. In general, the features of the type 1 map will correlate better with smaller geological structures, often ones of outcrop size for maps at a scale of 1:500,000, while those of type 2 correlate fairly well with features of regional scale.

The following procedure has evolved during the study that seems to give consistent results:

The criteria for choosing photolineaments must be clearly defined before any mapping is done. Giving two individuals identical photos with no instructions other than to produce a photolineament map will often result in two very different maps. When decisions are made in advance of mapping as to the type of feature and degree of connectivity to accept, these maps become much more similar, but still not identical. Some mappers will accept only sharp, well-defined lines (usually straight stream, valley or ridge segments) while others accept the less obvious tonal anomalies which cross ridge and valley. This distinction is generally determinable even on imagery at a scale of 1:1,000,000 and so will present little problem in criteria definition. Connectivity is the second factor causing differences between maps. Some mappers, particularly inexperienced ones, will ignore features produced by the alignment of discrete points. Also, in some cases a photolineament will be mapped as a single, connected line by one mapper whereas others will map it as a series of unconnected lines. Which of these alternatives will be chosen depends on the purpose of the map, but for the Appalachian area, the choice that produces the longer lines will produce a map which better correlates with the usual geologic map available, and the opposite choice produces a map which correlates better with field outcrop observations. See further discussion of this below.

Mapping should be done only near the center of the image. It was found that the density of photolineaments drawn near the edge of the imagery was much less than towards the center. It remains reasonable constant in about the center half of the image. In this study, most of the imagery was reproduced as 10 by 16 inch (25 by 40 cm) sheets, so the resulting maps are about 8 by 10 inches (20 by 25 cm). For coverage of larger areas, the mapping is planned so that the 8 by 10 inch maps are adjacent and the imagery prints overlap. Were the mapping to be done for the entire image on non-overlapping imagery, there would be a false reduction in photolineament density in the areas corresponding to edge areas of individual images.

Mapping time should be relatively short. It becomes very difficult to remain objective when working on a single image at length. The best results seem to be to map for about 15 minutes and then break off for at least 15 minutes. This is followed by another 15-minute mapping period. This avoids eye fatigue which tends to produce a bias in the mapping. After one has been working on the same image for longer periods, there seems to be a preference for lines parallel to those already drawn. Generally, the two 15-minute periods are sufficient to map photolineaments of an 8 by 10 inch area. If this limitation is not observed, it is possible also that too many photolineaments may be mapped.

Such maps may not be useful for any purpose involving choice of particular sites, although lineament density analysis can still be performed (Peterson, 1976).

The imagery should be observed from all angles. The image should be left movable during the mapping. If it must be mounted on a surface, this surface should allow one to walk around it. It is best to leave the image unmounted; if an overlay is to be used, it should be fastened to the photo rather than to the table so that the assembly can be moved as a unit. Most individuals have preferred directions of perception and fixing the relative viewing angle will produce a map biased in favor of these directions. Also, if the images are viewed by transmitted light on the conventional light table, the aligned light bars from the fluorescent tubes introduce an unwanted directional preference.

Factors Responsible for Map Differences

Even if all the potential variations in maps due to the operational problems discussed above are eliminated, there are still differences introduced by variations of the imagery. For any given area, there may be available imagery of many different types - black-and-white panchromatic and narrow band, color, color infrared, multispectral scanner, thermal, side-looking radar, etc. Each of these has a different appearance. Then within each type there are other variations - seasonal, time of day, and look angle. Having chosen an image to be printed as a base for mapping, there are then variations in print characteristics - scale, density, contrast, and sharpness of focus. All these factors in combination can provide a very great variety in the print from which the map is to be made. The differences produced by various factors are discussed below in detail. The more obvious difference were analyzed qualitatively, but several maps were produced for the test area in figure 9 for quantitative comparisons. The extent of the variation possible is illustrated by figure 10. Five representative maps were digitized and differences in length and orientation of the photolineaments between pairs of maps were statistically tested with the Wald-Wolfowitz Runs Test (Mardia, 1972). This test is based on the overall properties of the distribution of the variable tested rather than any one property.

Image scale. This variable produced the greatest variation between maps. For any given area, more photolineaments were mapped at the larger scale. The effect is approximately proportional to the scale; in essence, this means that the photolineament density is roughly the same on all maps (as long as the other factors remain constant). In the test case, there are about four times as many photolineaments on imagery at a scale of 1:1,000,000 as on 1:5,000,000 imagery and about two and one-half times as many on 1:500,000 imagery as on 1:1,000,000. The ratios of accumulated length are less, however, because the average length is much less on the larger scale imagery. In all cases tested, this difference in length was significant at $\alpha = 0.01$. Differences in orientation of photolineaments between maps of different scales are somewhat less. Only the comparison between the 1:1,000,000 and 1:500,000 imagery tested at a very significant difference. Inspection of the various maps gives a ready explanation of the differences. Two things were noted. First, a number of photolineaments aligned "en echelon" on larger scale imagery appeared as a single one on the smaller scale (see Figure 11a). Such "en echelon" features can occur at virtually all scales from those such as shown here down to microscopic size (Koide, 1971). Second, aligned but separate photolineaments on the large scale imagery tended to be mapped as a single, longer one on the small scale imagery (figure 11b). The first condition is responsible for differences in both length and orientation and the second for differences in length only. Therefore, one would expect a significant difference in length to be more likely than a significant difference in orientation. Also, the lowest degree

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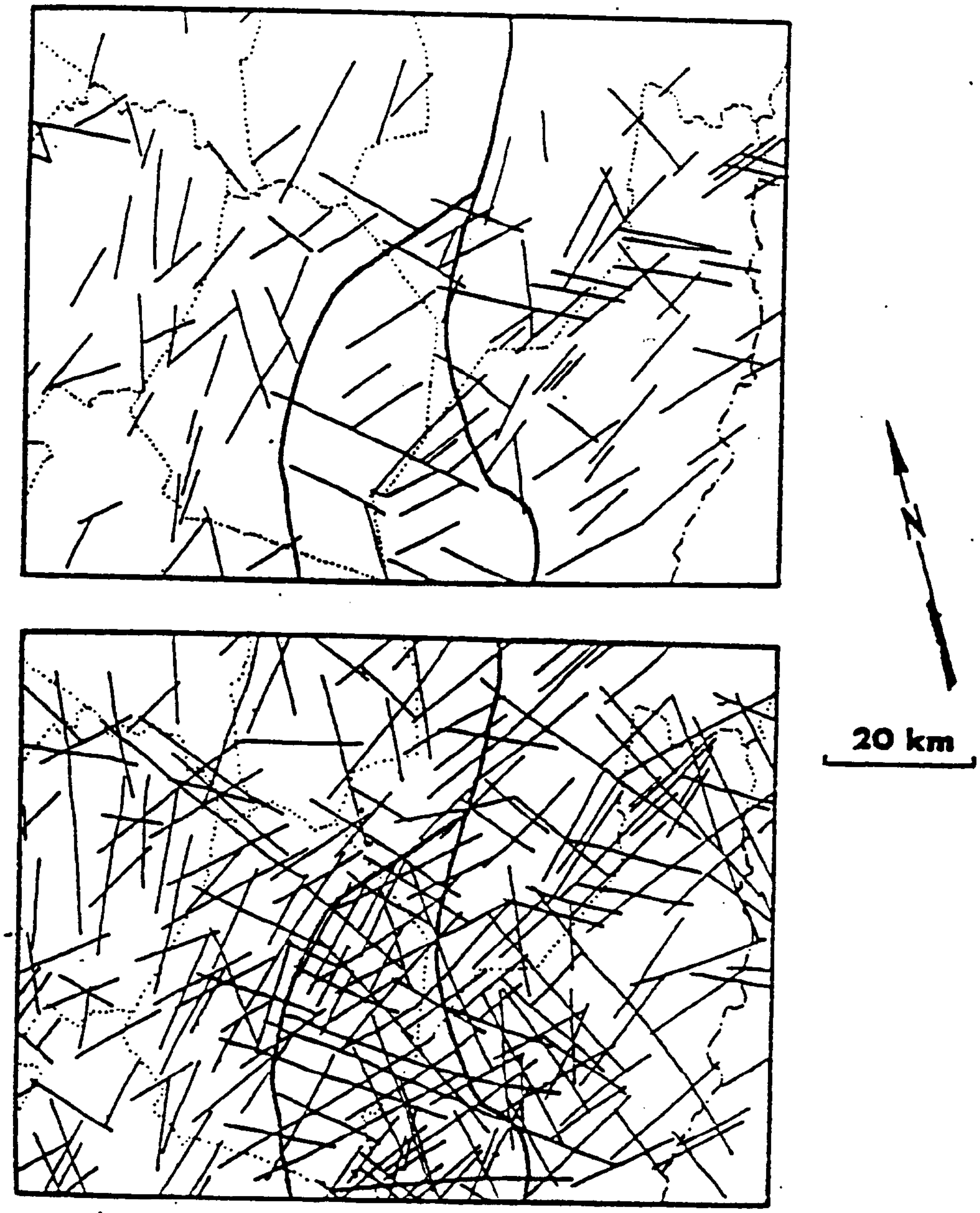

Figure 10. Two representative map examples from the photolineament test mapping area showing the type of variation which might be expected.

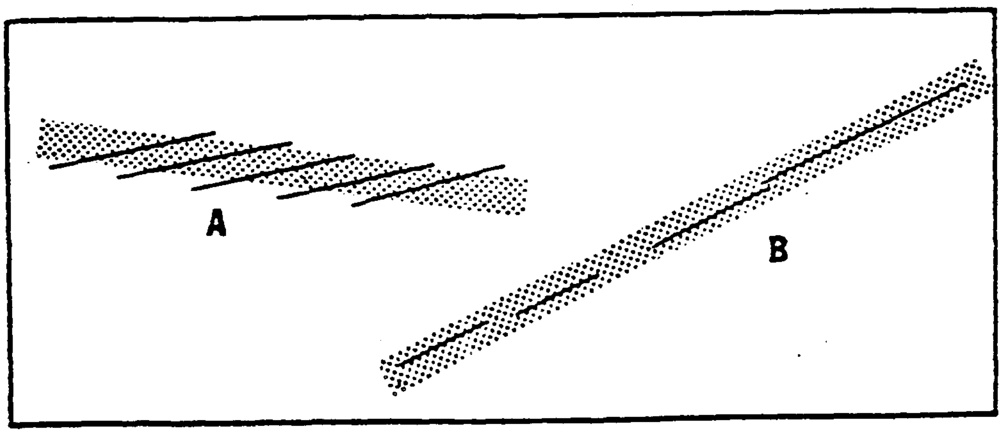

Figure 11. Illustration of the scale-change effect. The screen pattern shows a single photolineament mapped at one scale which might appear as shown by the solid lines at a scale an order of magnitude larger.

of positional agreement of photolineaments was found between maps produced from different scale imagery. Between pairs of maps of different scales, on the average only about 4% of the photolineaments were on both maps. The effects of smaller scale may be simulated to a large extent by a decrease in sharpness of focus of the print or by producing the type 2 map (see "Materials and Techniques" above). From this we may conclude that, in general, a loss of resolution produces the effect discussed in this section.

Image contrast. Images from Skylab and Landsat were selected and two prints of different contrast (one each on grade 3 and grade 5 photographic paper) were made. In the comparisons, there was no significant difference in length or orientation at $\alpha = 0.05$; average length was greater at $\alpha = 0.10$ on the higher contrast paper. The highest value for coincidence of photolineaments occurred for this comparison with an average of 10%. However, there were only about half as many photolineaments mapped on the lower contrast print.

In general, certain conclusions may be drawn on the basis of this data and qualitative judgements from other maps: anything which increases the actual or apparent contrast of an image will serve to increase the number of photolineaments present but will have little effect on their orientation and a marginally significant effect on their average length. Shifting from panchromatic to infrared, summer to winter, midday to morning or evening imagery will all serve to increase the apparent contrast and to have similar but not quite identical effects to that of increased print contrast.

Image density. In general, a "normal" density print allowed for the mapping of the greatest number of photolineaments. Either increasing or decreasing the density tended to eliminate the shorter and less prominent ones. Light image density seems to be a desirable characteristic for selecting relatively few, relatively long photolineaments.

Image type. This is relatively complex factor in that it combines all of the above factors plus others. As image type is changed, say from Skylab to Landsat, several factors operate at once. For example, the imagery used in the quantititive comparison for this study is Skylab summer and Landsat winter thus introducing the factor of seasonal change. Sun azimuth and elevation are different, thus producing shadows of different length and orientation. Skylab is photographic coverage and Landsat is multispectral scanner. All these factors serve to complicate the analysis. It is interesting to note, therefore, that there is little or no difference shown by statistical comparisons. For the two maps produced from prints of the same contrast, density and scale, but different satellites, an average of 6% of the photolineaments are on both maps. This is greater than the figure for some map pairs which differ only in scale. There was no significant difference detected in either orientation or length.

When photolineament maps are to be applied to specific tasks, certain preliminary planning is required before mapping is begun. For hydrocarbon exploration in fractured rocks, towards which this entire project is directed, the following may be an appropriate procedure. The methods have not yet been tested in a practical way, but are based on the data now available. First, one would select only areas that are geologically promising. Then several photolineament maps should be made. Generally, one would require a map of regional scale to determine where zones of fracture zones would be likely. Then a map of larger scale for selected areas of such zones would be made to determine single fracture zones. An area would again be selected, and a larger scale map made to select drilling sites on single fractures. At all times during this process, the geologic and economic factors must be considered. Thus, the photolineament maps should be used only as an aid and not a controlling influence. At the present time the relationship between photolineaments and actual rock fractures is still poorly known, and this can change only through careful mapping, both of photolineaments and of fractures.

Section 2 Fracture Systems in Mineral Production

It has been long known that fractures and fracture zones play an important part in the emplacement and production of many mineral resources. The presence of hydrothermally emplaced minerals in fractures is common. Much of the lead, zinc, and fluorite production is from fracture filling. For instance, the crevice deposits of fluorite from Cave-in-Rock and Rosiclare, Illinois, are well known. The lead and zinc deposits of the Joplin, Missouri, and Galena, Illinois district are commonly fracture fillings. Even the stratiform fluorite deposits of southern Illinois may have been deposited by waters rising through vertical enlarged fractures.

The fractures could have numerous causes for their origin. Most are probably related to larger structures created by regional or local tectonism. In one study on the use of photolineaments for mineral exploration in Colorado, Nicolais (1974) makes the assumption that (mineralization [of metallic mineral deposits] is probably structurally related to faults and shear zones, which may, in turn, be spatially related to intrusive stocks, plugs and volcanic centers." This particular situation is treated theoretically by Koide and Bhattacharji (1975) who show the fracture patterns which might be expected and how mineral deposits might be distributed.

In addition to the basic deposition of mineral veins in fractures, many mineral deposits have been found aligned along major fracture zones, and in particular the intersections of two or more such zones. That mineral deposits occur in belts has been long known. Stokes (1968) describes the characteristics of the mineralized belts of Utah. The mineral deposits are

are developed along three well-defined zones. Individual deposits are preferentially formed along faults which are generally parallel to the belts. Thamm (1969) discusses the elongated mineral deposits of Africa and their alignment along straight lines (great circles). These lines are at least parallel with regional fracture systems. He concludes that the mechanism producing fracture systems and that emplacing mineral deposits must have some common causes. Kutina (1975; 1976) shows the relationship between metallogenic deposits and fracture zones. There is a general clustering of the deposits at the intersections of the structural lineaments (fracture zones).

In most of the Appalachian Basin, solid mineral fracture deposits are not of as great an interest as the fluids. The initial practical utilization of fracture and photolineament investigations was in selecting sites for water wells in carbonate terrains (Lattman and Parizek, 1964). It was found that water well-yields increased dramatically at short photolineaments (fracture traces) and particularly at their intersections; often the increase was as great as one or two orders of magnitude. Further work which included the investigation of other factors has indicated that, at least in certain carbonate terrains, expected water well yields could be greatly improved by use of fracture trace maps (Siddiqui and Parizek, 1971). Additional work by Cline (1968), Moore (1977), Holland, Rauch, and Werner (1977) and others has extended this concept to non-carbonate terrains as well. Clearly, aquifers in rocks of low bulk permeability will only be productive if the rock is fractured. The investigations mentioned above were directed primarily toward such rocks. Further details on the interrelationship of ground water and fractures are to be found in Parizek, White, and Langmuir (1971).

Of considerable value at the present time are the other mineral fluids - hydrocarbons. Many areas of the world have considerable oil or gas in rocks of extremely low permeability, particularly mudstones of various types. For example, Harnett (1968) describes the characteristics of the Niobrara Formation of Wyoming and Colorado. This is a very oily formation which is primarily a calcareous shale. Production is assumed to be from fractures which are known to exist in dimensions ranging from hairline cracks to major cavern size. Prospecting for well sites on the basis of fracture development has met with some success.

Natural gas is also found in rocks of very low primary permeability. Of particular interest at the present time is the rather large amounts locked up in the Devonian shales of the Appalachian Basin. Hunter and Young (1953) describe the relationship of natural gas production to fractures. Although there is a minor permeability system in some of the silts and fine sands of the shale, such zones contribute little to production. Gas is released from the rock into fractures which provide the major permeability conduits to wells.

Prospecting for fractures has taken a number of forms. Harnett (1968) described several methods of locating promising fractures, ranging from computational methods based on location of flexing and elongation on folds to locating calcite-filled fractures by bulldozing the surface and then projecting these to the depths of pay zones. He reports variable success because of some problems. The major one of these problems is related to the nature of fracture propagation. Fractures, once initiated, are likely to propagate along a plane only if the rocks are of relatively uniform competency. Where this is not the case, such as when massive sandstone beds, and lenses are within a predominantly shale formation, the propagating fracture is likely to be refracted. In this case any geometric projection is likely to give an erroneous location. Particularly if the pay zone is at great depth, such a computed location might not be even close to the true location.

Because of the depth of the reservoir, the above methods of fracture prospecting are of little practical value in the Appalachian Basin. Ryan (1976) reports on a project of fracture mapping using remote sensing methods to develop the Haysi gas field in the Berea sand which, although a sand, is so fine as to have a rather low permeability and produces mainly from fractures. The field is located in eastern Kentucky and western Virginia near the eastern end of Pine Mountain (see figure 2). The method involved mapping of photolineaments on satellite and side-looking radar imagery. Wells drilled within 1500 ft of one of these photolineaments yielded, on the average, at twice the rate of those drilled farther away.

It is apparent that photolineaments may be indicators of fractures which improve production of both hydrocarbons and ground water. Therefore, similar techniques should be useable in prospecting for these fluids. There are some fundamental differences, however. Harnett (1968) mentions one such difference. The clays of the Niobrara are not affected by the oil; however, water causes them to swell and close. The basic and most important difference is in the characteristics of the fulids themselves. Of all the fluids, water has the highest specific gravity. Oil and gas are lighter; in fact, gas is generally even lighter than air. Thus, where to find water in fractures we need only find a fracture system or zone connected to a source of water, for oil or gas we need not only a fracture system and source of oil or gas, but also a seal above to keep ground water from displacing the oil or gas and/or to keep air from displacing gas. This problem will be further discussed in Chapter 3.

Section 3 Relationship of Fractures, Joints, and Photolineaments

A considerable body of literature exists on this subject. There have been published hundreds, if not thousands, of papers relating surface fractures or joints to photolineaments and topographic lineaments. There is a significant division of the reports into three classes: 1) reports of same patterns for surface fractures and photolineaments, 2) reports showing different patterns for the two features, but having a clear, consistent relationship to each other, and 3) reports of no apparent relationships.

One problem surfacing time after time in the literature is the inconsistency of the comparisons. Since most of them have been graphical comparisons, they may not be statistically valid (Werner, 1976b). Furthermore, depending on how the orientation diagrams were produced, statistically similar distributions may appear quite different (see Chapter 4).

"Parallelism has been recognized between fracture trace orientation and joints in relatively underformed bedrock of Pennsylvania age of the Appalachian Plateau (Lattman and Nickelson, 1958) and flat-lying rocks elsewhere (Hough, 1960; and Boyer and McQueen, 1964). In folded rocks fracture traces and joints have been found to have different trends (Lattman and Matzke, 1961; Keim, 1961). These authors found that joint sets are parallel and perpendicular to the strike of bedding in Nittany Valley, and that fracture traces are unrelated to local fold and fault structures. Dominant trends of fracture traces and joints differ; fracture traces appear to be unaffected by strong compressional folds and tend to lie at a constant (52°) angle to regional structure. This work, together with that of Calkins (1967) and Lattman and Segovia (1961), supports the conclusion that fracture traces are not controlled by local structure but rather by regional features. Trainer and Ellison (1967) found that fracture traces in the Shenandoah Valley of Virginia, are primarily controlled by structure and lithology. Lithology and solubility of rocks shows a strong control on the abundance and lengths of fracture traces but not on their orientation" (Parizek, 1971, p. 30).

Henderson (1960) studied air-photo lineaments in east Africa and found many of them to be related to fractures in some way. Many are due to incised fractures; that is, erosion - either fluvial or weathering has cut into some joints and faults to give straight and narrow valleys. He is also one of very few people to note the presence of positive lineaments due to fractures - mineralized by a resistant material, in this case. Other references to positive lineaments are Flint et al. (1953) and Tjia (1962). Both are cases of limestone in tropical areas which has been case-hardened by frequent alternating wetting and drying cycles. This process has been active in prominant near-surface fractures and subsequent erosion has caused these fracture zones, although still open, to stand up.

Brown (1961) presents some comparisons between joint sets and photo-lineament sets for central Texas. He finds that about two-thirds of photo-lineament sets correspond to joint sets. However, the most prominent sets not generally correspond to each other and they usually differ by more than 20°.

Hine (1970) found a parallelism between fracture traces (short photo-lineaments) and joints in central Kentucky. He concludes that the fracture traces are formed through solution along major joints in the carbonate rocks. However, the method of comparison used rather generalized graphical summaries of the data and these conclusions are not at all apparent from the presentation in the paper. The peaks he shows on his diagrams do not show any pronounced similarity.

Babcock (1973, 1974a, 1974b, 1976a) has studied joints and short photo-lineaments of the partially drift-covered terrain of Alberta. He has found a general coincidence of two major peaks - one along bedrock and strike, one across bedrock and strike - of both outcrop fractures and photolineaments. The comparison is not entirely certain, however, and the peaks may differ by as much as 20°.

Comparisons of a similar nature have been done in the Appalachian Plateau of southern New York and northern Pennsylvania by Overbey (1969) and in eastern Ohio by Overbey and Rough (1971) and Komar et al. (1971). Similarities appear; however, since these are graphical rather than statistical comparison, they are somewhat uncertain.

Kowalik and Gold (1976) report a "crude directional correspondence of cross strike lineaments with major joint trends. Subsequent work at the Pennsylvania State University Remote Sensing Laboratory (Gold, personal communication, 1976) indicates that such parallelism may be strongly scale-dependent. It was found that there is a perpendicularity between features which differ in scale by about an order of magnitude. Thus, one would expect parallelism between features differing in scale by two orders of magnitude. The Pennsylvania State University group has worked throughout the state of Pennsylvania and thus their work extends through the Valley and Ridge and the Plateau provinces; however, their major consideration was of the folded rocks.

Work in the carbonate rocks of the eastern-most portion of the Appalachian Plateau of West Virginia (Werner, 1975) shows a rough parallelism of one or two major fracture directions to the nearest of the longer photolineaments. Short photolineaments (i.e., less than 10 mi.) were not generally considered so the difference in scale is probably at least two orders of magnitude. Figure 12 shows the photolineament map and rose diagrams of six of the outcrop fractures used for that study. Further work in that terrain but not included in the paper indicates that a similar parallelism exists between outcrop

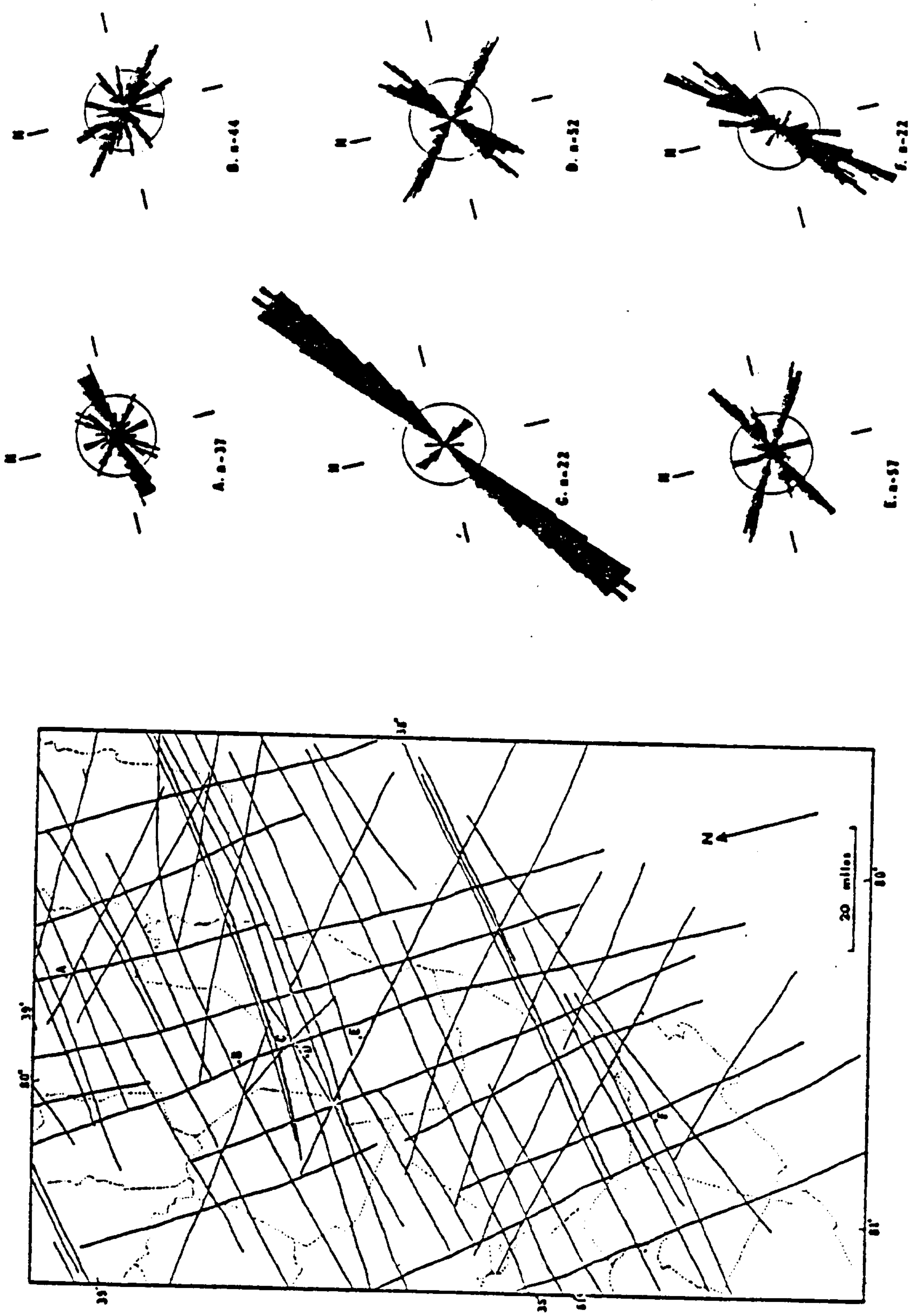

Figure 12. Photolineament map of eastern West Virginia and rose diagrams of surface fractures within the area (from Werner, 1975).

fractures and photolineaments averaging 0.5 miles to 5 miles long.

Hodgson (1967a) discusses the reasons for possible parallelism of photolineaments and fractures. He shows the relationship between outcrop fractures, "master joints", and fracture zones. In general, fracture zones may be seen as closely spaced fractures. These seem to occur with some periodicity similarly to the single fractures themselves. If this concept is extended to smaller and smaller scales, then the regional photolineaments may be composed of closely-spaced, parallel or subparallel short lineaments which in turn are composed of similarly arranged fracture zones.

The main interest of the hydrocarbon industry in fractures is in natural and induced fractures in the pay zones. Subsurface fracture data is relatively scarce since it is difficult and expensive to obtain. A few studies have been made of the relationship of subsurface fractures obtained from well bore studies and cores to surface fractures or photolineaments. Komar et al. (1971, 1973), Overbey (1969), Overbey and Rough (1973), and Overbey, Sawyer, and Henniger (1974) all show similar distributions for both surface and subsurface fractures. Several peaks are common to the pairs of distributions compared. However, because these comparisons are purely graphical and not statistical, it cannot be determined how strong these relationships may be. A study of a similar nature by Babcock (1976b), however, indicates that such relationships may be statistically significant. He found common peaks for bedrock joints in rocks of considerable variation in both age and type. These peaks are within a confidence interval of 90% (i.e., $\alpha = 0.1$).

Section 4 Jackson County Fractures

In order to test the relationship between surface fractures and photolineaments, data was collected from outcrops throughout a test area primarily in Jackson County, West Virginia over and near the Cottageville (Mt. Alto) gas field. Morgantown Energy Research Center personnel obtained readings of outcrop fractures at 40 sites. During the summer of 1977, an attempt was made to relocate these sites and thirty-three were revisited and the remainder could not be located. In addition, eight additional outcrops were found and measured. In order to check the comparability of data between operators, two of the original thirty-three stations were measured, and, in both cases, were found to be not statistically different at $\alpha=0.1$. Thus it is reasonable to combine the data sets which has been done in figure 13 and plate 1.

There were, however, certain problems encountered, primarily because of the surface geology of the area. In Jackson County, the surface rocks are of the Permo-Pennsylvanian Dunkard Group which is primarily a deltaic sequence consisting of gray and red mudstones, siltstones, and channel and bar sandstones. The most prevalent rocks in outcrop are the sandstones. There are several reasons why fractures measured on these sandstones may not be reliable indicators of regional fracture patterns. The sandstones tend to be relatively small patches surrounded by the mudstones. This leads to two conditions. First, regional fractures may not be propagated through the mudstones into the sandstones. Thus, fractures seen in the sandstones may well be due to fracturing of a brittle mass only poorly supported by the surrounding, rather weak mudstones and breaking up under its own weight. Second, the irregular shapes of the sandstone bodies can cause refraction of a propagating fracture and so change its orientation by twisting the propagating wave front about an axis parallel to the direction of propagation. In this case, although the fractures are related to regional fracture patterns, the directions found tend to differ from that pattern.

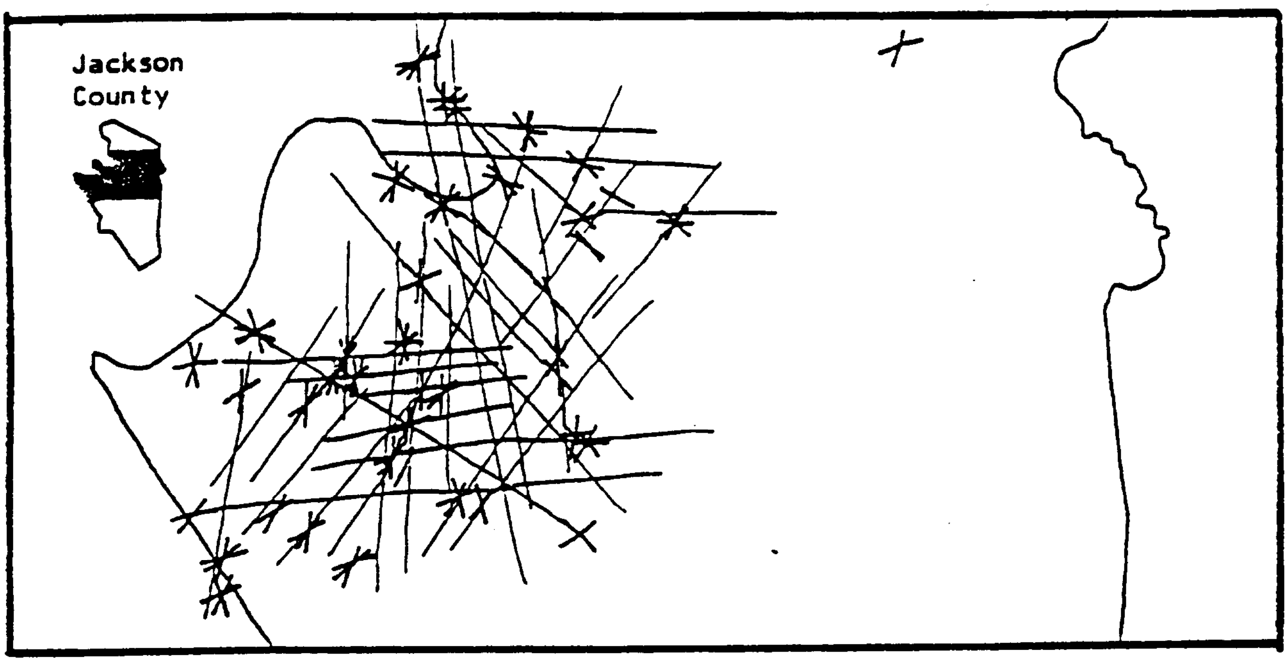

Figure 13. Prominent surface fracture directions in the area of the Cottageville gas field in Jackson and Mason counties.

The effects of these problems are partially reduced by a regional analysis employing several thousand measurements. With this quantity of data, errors introduced by factors active in small areas are eliminated or greatly attenuated. In any case, however, any analysis done cannot depend on a small error margin.

Results. Figure 13 shows the most important preferred orientations at outcrops in the general area of the Cottageville Gas Field. Figure 14 is a summary of the more prominent photolineaments of the same area as the joint measurements. A comparison of figures 13 and 14 shows that several of the trends are coincident. The major preferred directions on both diagrams are approximately the same. There is, however, clearly not complete agreement between the two patterns. Assuming a relationship between the two types of features, the disagreement between the two sets of orientations could be caused by either 1) the distortions of joint directions by sand lenses as outlined above, or 2) a difference in reaction of the short (joints) and long (photolineaments) features to regional stresses which may have varied in direction. There is, however, too much coincidence of the orientations of the two sets of data for it to be ignored entirely. Thus, it appears that the photolineament maps may serve to at least partially predict surface outcrop fracture directions.

Predicting subsurface fracture orientation from photolineaments is less certain. It is difficult to evaluate this relationship mainly because of the lack of data. Very little subsurface data on fractures is available for the Cottageville gas field area. Only the data derived from one core (published by Patchen and Larese, 1976, p. 16-17) was obtained and used. However, in the vicinity of the core from which the subsurface orientation measurements were taken is one outcrop site. The relationship between the two sets of orientation

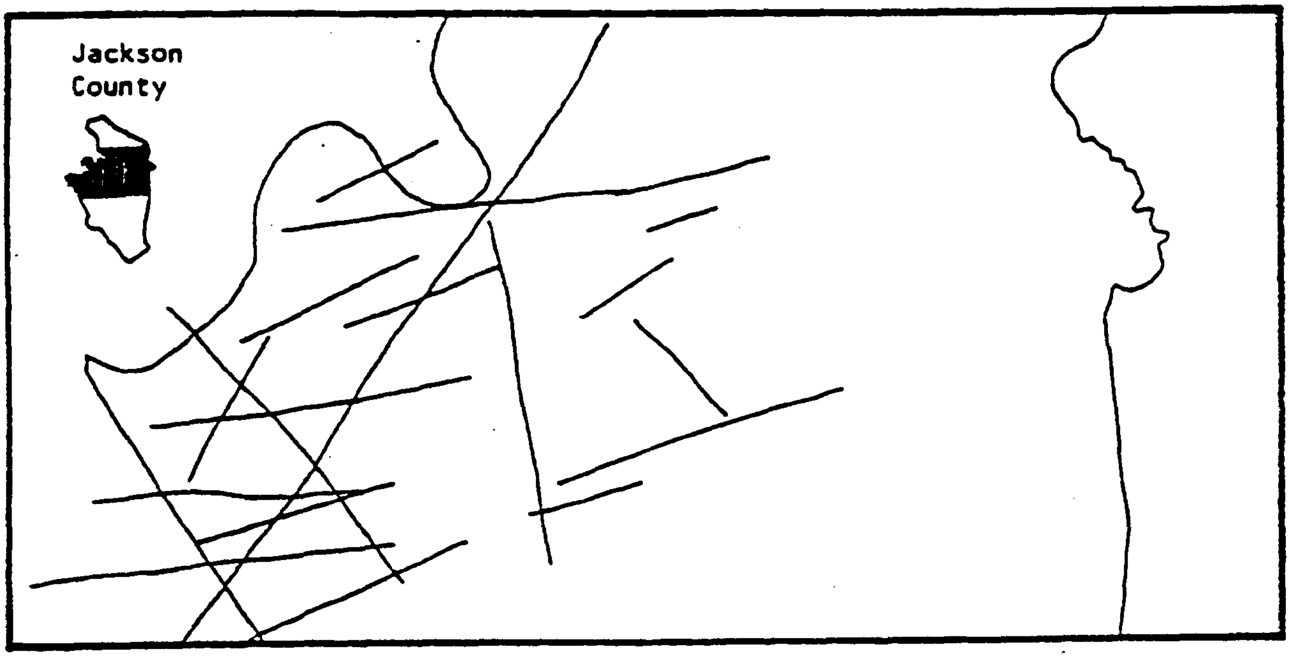

Figure 14. Prominent photolineaments of the area of the Cottageville gas field.

measurements is not clear-cut, but at least one of the major directions of the surface outcrop matches the chief subsurface fracture orientation. From this meager evidence, one may postulate a relationship between surface and subsurface fractures, and indirectly between subsurface fractures and photolineaments. Such a relationship needs extensive testing, however, before it can be applied as a predictive tool. The additional step of predicting subsurface fractures induced during stimulation of wells is even less certain because of additional restrictions placed on their formation by conditions under which they form.

Clearly, the poorly developed fractures and the heterogeneous geology of this area makes this area probably one of the worst in the entire Appalachian Basin for a study such as this. In spite of this, the regional patterns are still discernable, though somewhat dimply. It may be safe to say that if correlations can be found here at all, they would be far clearer in other, better suited, terrains. Studies are currently underway under DOE Contract EY-76-C-05-5194 which should greatly extend the knowledge of these comparisons. A considerable amount of data has and will continue to be gathered regarding surface and subsurface fractures.

Section 5 Photolineament Trends

Numerous photolineament maps were produced in the course of this study. A general map for the entire study area (figure 15) shows general trends. It is obvious from this figure that many photolineaments are of considerable extent, crossing from one geological province to another. There are five prominent directions apparent in the overall study area; these are approximately N 75°E, N 12°W, N 40°E, N 55°W, and N 70°W. Not all these trends are

Figure 15. (page 43) Photolineaments derived from satellite imagery for eastern Kentucky and southern West Virginia.

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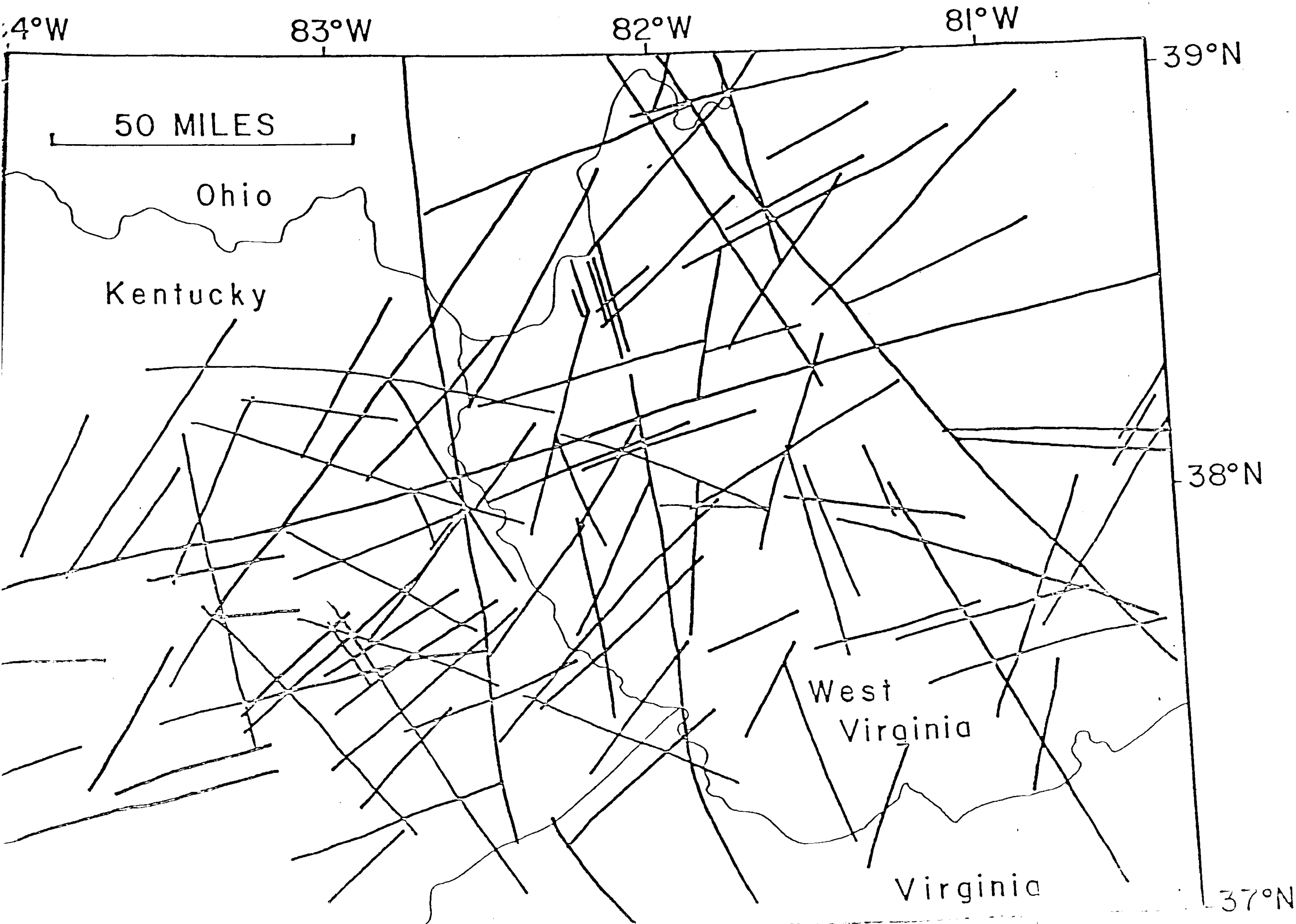

everywhere present, however. The first three trends seem to persist; the last two do not. Figures 16 and 17 are rose diagrams of photolineament trends from two overlapping Landsat frames along the West Virginia-Ohio and West Virginia-Kentucky borders. All peaks match between the two patterns. On the other hand, figure 18 includes an area more to the east--essentially the map shown in figure 12--and there is some difference here: the N 55°W peak is absent and a N 70°W peak appears. Although it is not entirely clear, it appears that the persistent trends--N 75°E, N 12°W, and N 40°E--may be basement geology related. The N 55°W trend may bear a cross-strike relationship to the Southern Appalachians--the Landsat images used for figures 16 and 17 include such Southern Appalachian features as the Pine Mountain fault block. The N 70°W trend is cross-strike to the Central Appalachian fold belt which is included in part of the map area from which figure 18 is derived.

Further evidence of these trend associations is shown by the photolineament maps for Wayne and Jackson counties (figures 19 and 20). The area of both these counties apparently is isolated from the effects of the Appalachian folding. It is west of the Burning Springs Anticline--generally considered the westernmost of the Central Appalachian folds--and north of the Warfield Anticline--possibly the northernmost of the Southern Appalachian features, although that is not entirely certain. Neither the N 55°W nor the N 70° W trends are prominent on the two photolineament maps although short segments can be found.

Somewhat contradictory evidence is seen in figure 21, however. This photolineament map is in the Hazard, Kentucky area which should be clearly out of the influence of Appalachian tectonics. However, all five of the aforementioned trends appear fairly prominently in this figure.

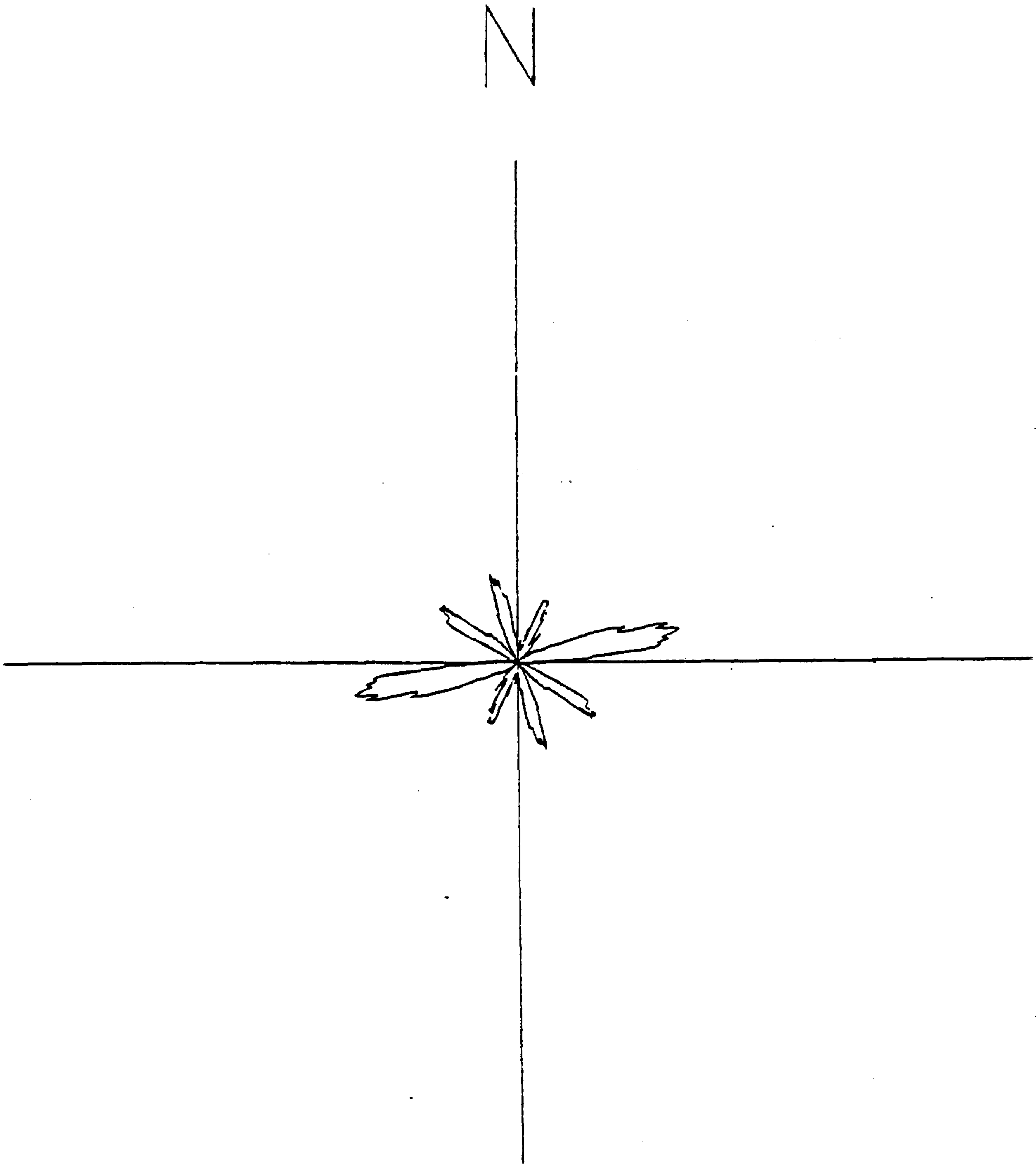

Figure 16. Rose diagram of photolineament orientations mapped from a Landsat image approximately centered on the Jackson County, West Virginia, area (NASA image ERTS E-1173-15364, 12 January 1973).

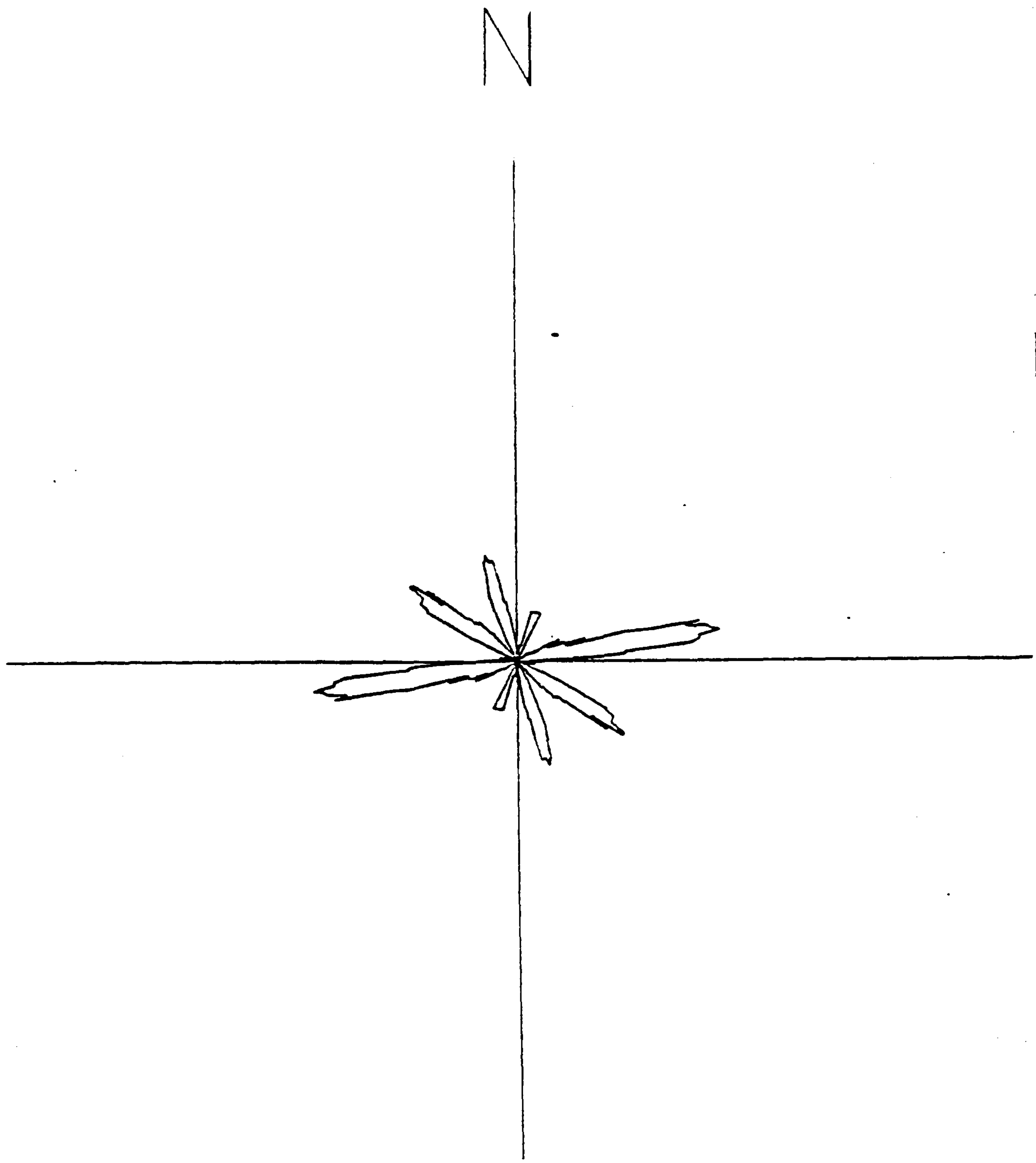

Figure 17. Rose diagram of photolineament orientations mapped from a Landsat image centered over Wayne County, West Virginia (NASA image ERTS E-1498-15400, 3 December 1973).

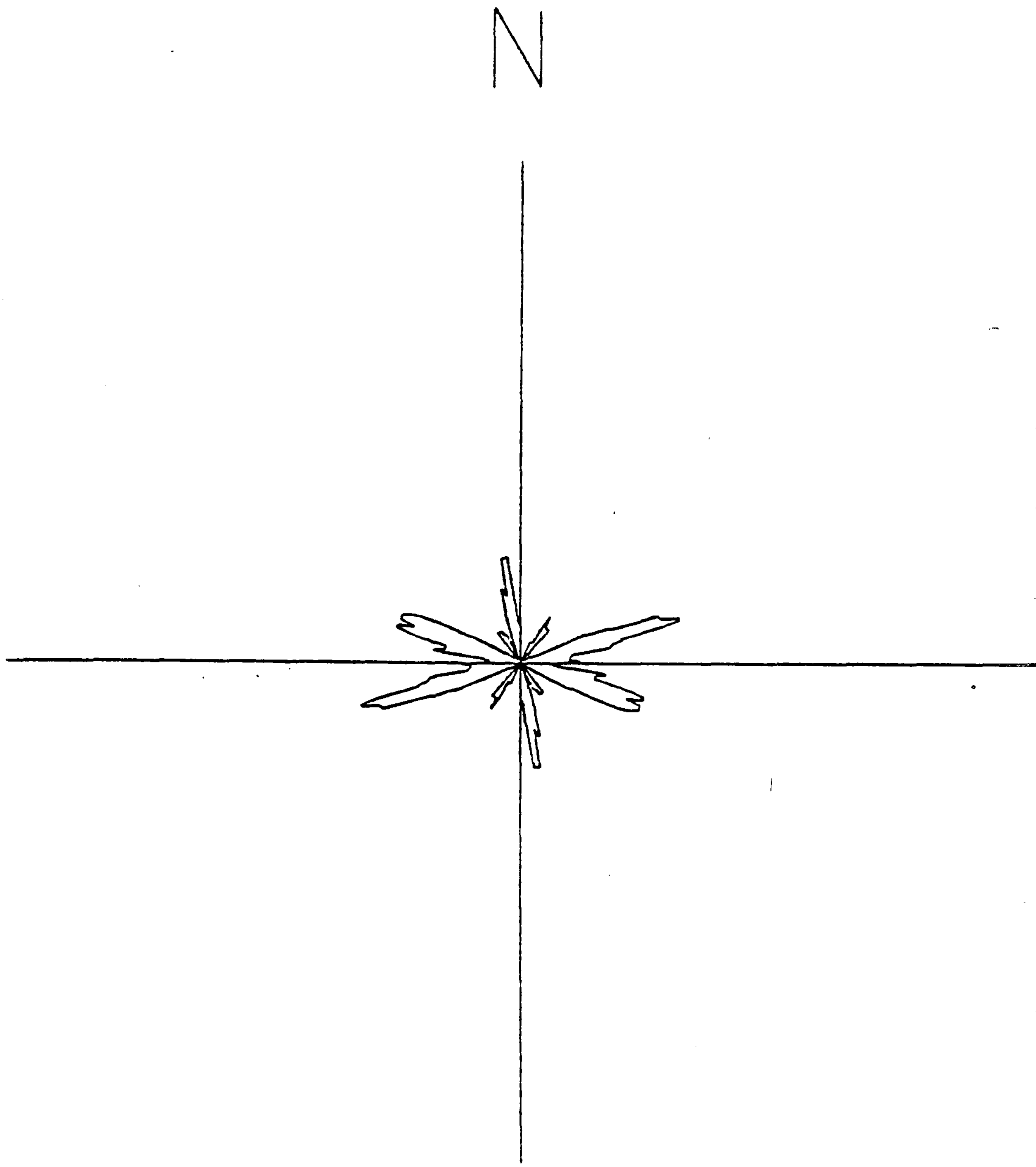

Figure 18. Rose diagram of photolineament orientations mapped from several Landsat images across most of southern West Virginia.

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Figure 19. (page 49) Photolineaments of Wayne County, West Virginia. Shown are only those lineaments which appeared on at least two maps of the four produced from various satellite images.

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Figure 20. (page 51) Photolineaments of Jackson County and a portion of Mason County, West Virginia. The photolineaments shown appeared on at least two of the six maps produced from various satellite images.

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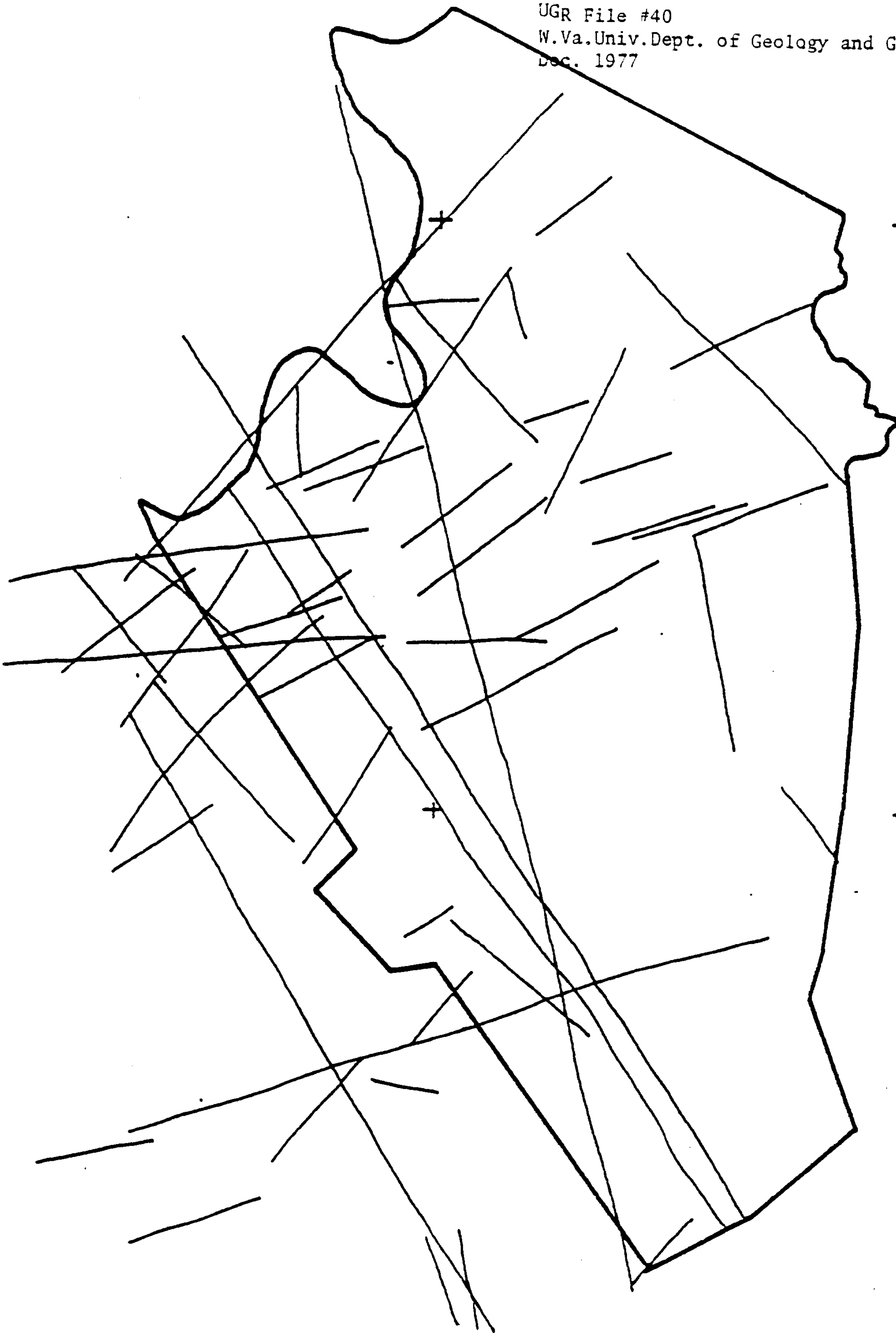

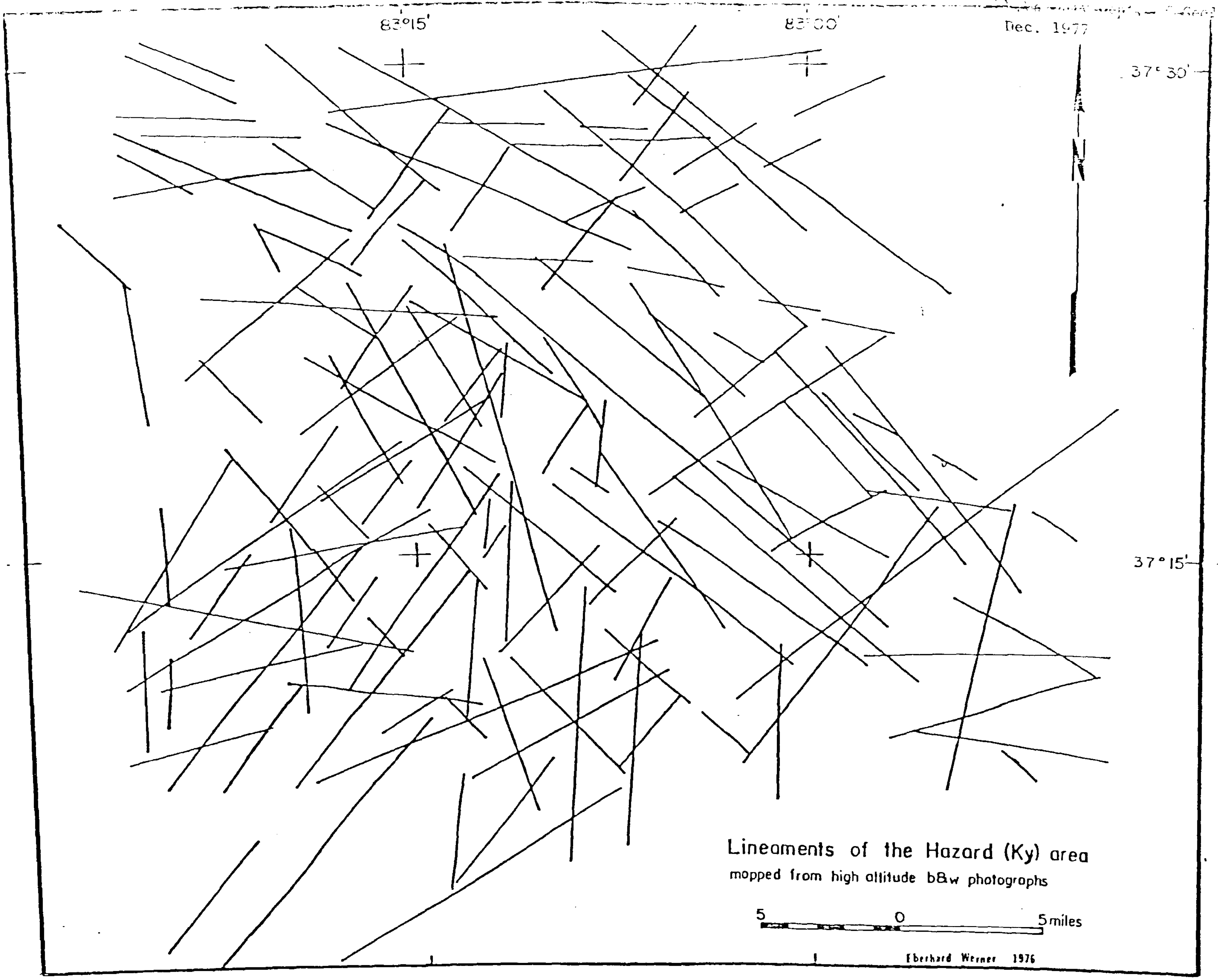

Figure 21. Photolineaments of the Hazard (eastern Kentucky) area derived from a mosaic produced from high altitude black-and-white aerial photography.

Section 6 Geology and Photolineaments

The discussion in this section is primarily confined to a group of very prominent photolineaments which cross much of eastern Kentucky and all of West Virginia, and which are considered associated with the 38th Parallel Lineament zone of Heyl (1972).

Numerous photolineament maps were produced for areas which include all or part of the postulated 38th Parallel Lineament in West Virginia. An example of these is shown in figure 22. This map shows only prominent, very long photolineaments which can be seen on the mosaic produced by the U.S. Soil Conservation Service from Landsat imagery. Several of the photolineaments fall on or near the line shown by Heyl. In general, on all of the photolineament maps produced, there is a concentration of photolineaments which are approximately parallel to and near the projected 38th Parallel Lineament. On most of the imagery studied, those photolineaments thought to represent the extension of the 38th Parallel Lineament are very prominent and often the most prominent in West Virginia. Generally, the relative prominence of any given photolineament in comparison to any other photolineament will change with changes in image characteristics such as scale, density, or contrast (Werner, 1976a) or with imagery which is taken at different seasons or times with resultant different sun azimuth or elevation (Kowalik and Gold, 1976). There are relatively few photolineaments in West Virginia which consistently remain prominent through these various changes; most of these comprise the group associated with the 38th Parallel Lineament. This group of photolineaments is present in a belt about 30-50 km wide across the state of West Virginia. This then may also be the size of the zone in which the 38th Parallel Lineament influences various geological factors.

The two photolineaments indicated in figure 22 are also approximately the northern and southern boundaries of an unusually dense concentration of

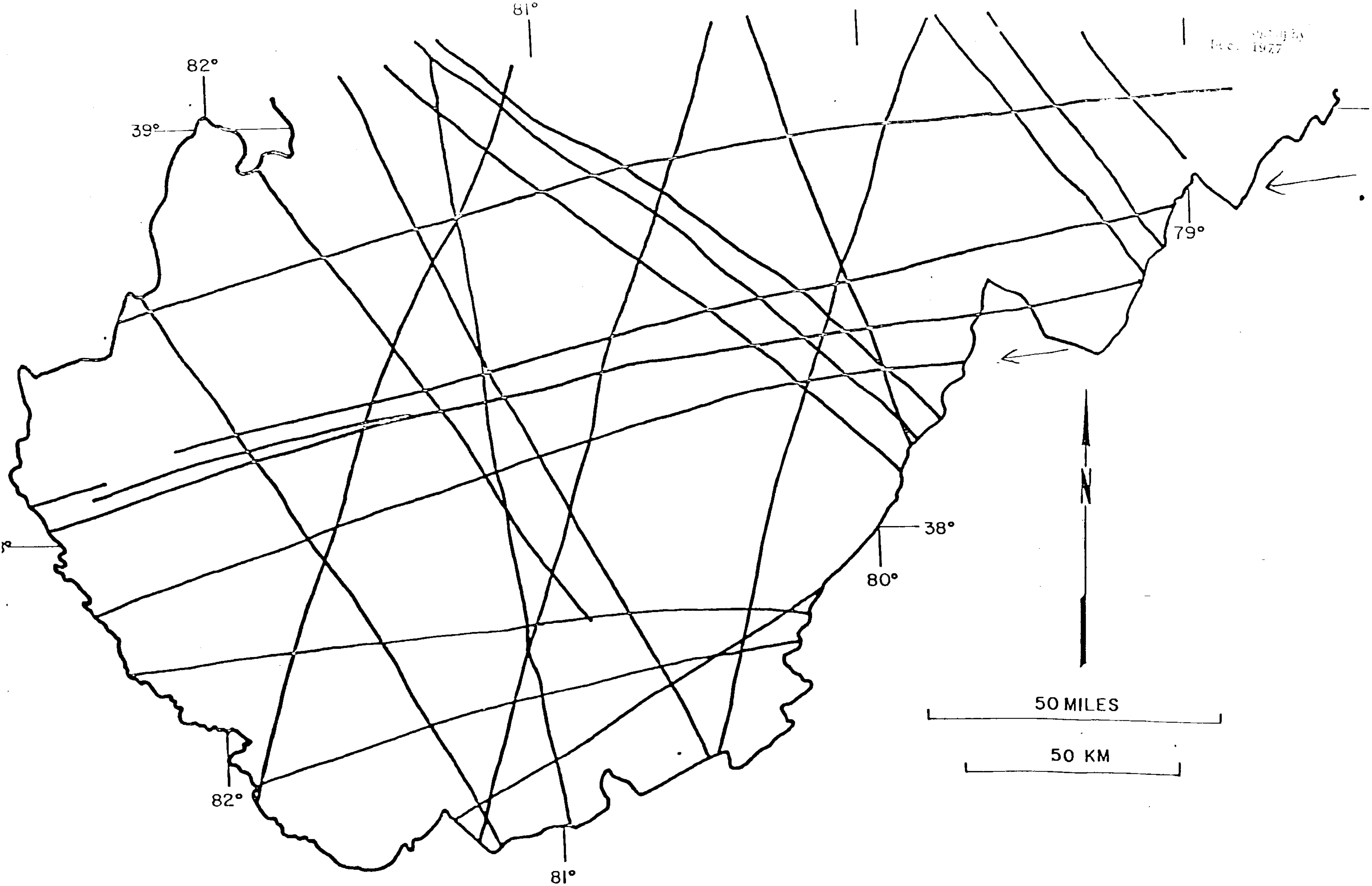

Figure 22. Photolineament map of the southern two-thirds of West Virginia. The most prominent photolineaments visible on the 1:1,000,000 mosaic constructed by the U. S. Soil Conservation Service are shown. Arrows point to the northern and southern boundaries of the 38th Parallel Lineament zone.

photolineaments mapped from imagery of all scales. In several maps done at scales of 1:125,000 or larger, there is an increase in photolineament density within this area over that 100 km to the north which is as much as an order of magnitude. It is unlikely that such a great increase is due only to imagery factors. It is therefore likely that the two indicated photolineaments are a reasonable indication of the boundaries of a geological domain which differs from the area around it.

Several aspects of the geology of the area under study were checked for their relationship to photolineaments in general and for their relationship to the 38th Parallel Lineament zone.

Structural Relations: In the initial investigation only terminations or abrupt bends of anticlinal axes in relation to a selected set of photolineaments were considered (Werner, 1975b). The structural data was that of the map of Rodgers (1970), and the photolineaments were the prominent set oriented near N 65°E and N 15°W in West Virginia and Pennsylvania west of the Allegheny structural front. It was found by application of the Chi^2 test ($\alpha = 0.001$) that the terminations or bends of the anticlinal axes were more likely to fall near one of the photolineaments than near a set of lines drawn at the same azimuth and average spacing as the photolineaments but in random positions. This suggests a possible relationship between photolineaments and the location of anticlinal-axis terminations or bends.

The present investigation is an extension of the above mentioned one. In particular, points on geological structures which might fall under the general classification of points of structural change, hereafter termed structural points, were mapped. Structural points include features such as terminations of fold axes and faults, bends (in this case any changes of azimuth greater than an arbitrarily chosen 15°) of fold axes or faults, and abrupt changes in the height of a fold. An initial map of these points was produced using data available from several stratigraphic horizons. However, for the final analysis all but the surface structures were ignored, primarily because of inadequate or uneven control information for all subsurface horizons. Most structural points were chosen on the basis of information from Shumaker's (1975) Coal Formline Map and a few were obtained from the West Virginia Geological Map (Cardwell et al., 1968). These points are shown in figure 23 and a contour map of the density of these points is shown in figure 24. The highest density of points indicated in figure 24 falls within the 38th Parallel Lineament zone. It occurs where the Lineament is intersected by a prominent photolineament zone which is oriented at about right angles to the 38th Parallel Lineament and which is clearly visible on most of the small-scale satellite imagery.

The relationship of the distribution of the structural points to the prominent photolineaments and to the 38th Parallel Lineament was analysed statistically by the use of the Chi^2 test. In the first case, structural points within 1 km of a photolineament were considered to be on it. Of the 187 points on the map, 69 fall within the area defined above. The total area covered by the 2-km-wide photolineaments in figure 22is 7425 km^2. This is about 25% of the 30,000-km^2 total area of the map, so the expected number of points if the distribution were random is 48. The Chi^2 test indicates that the observed number is greater than expected for the random distribution at $\alpha<0.001$.

The other relationship tested was the observed distribution of structural points around the 38th Parallel Lineament zone. Of the 187 structural points, 86 fall into the 9300-km^2 zone. The random expectation is 60, and the Chi^2

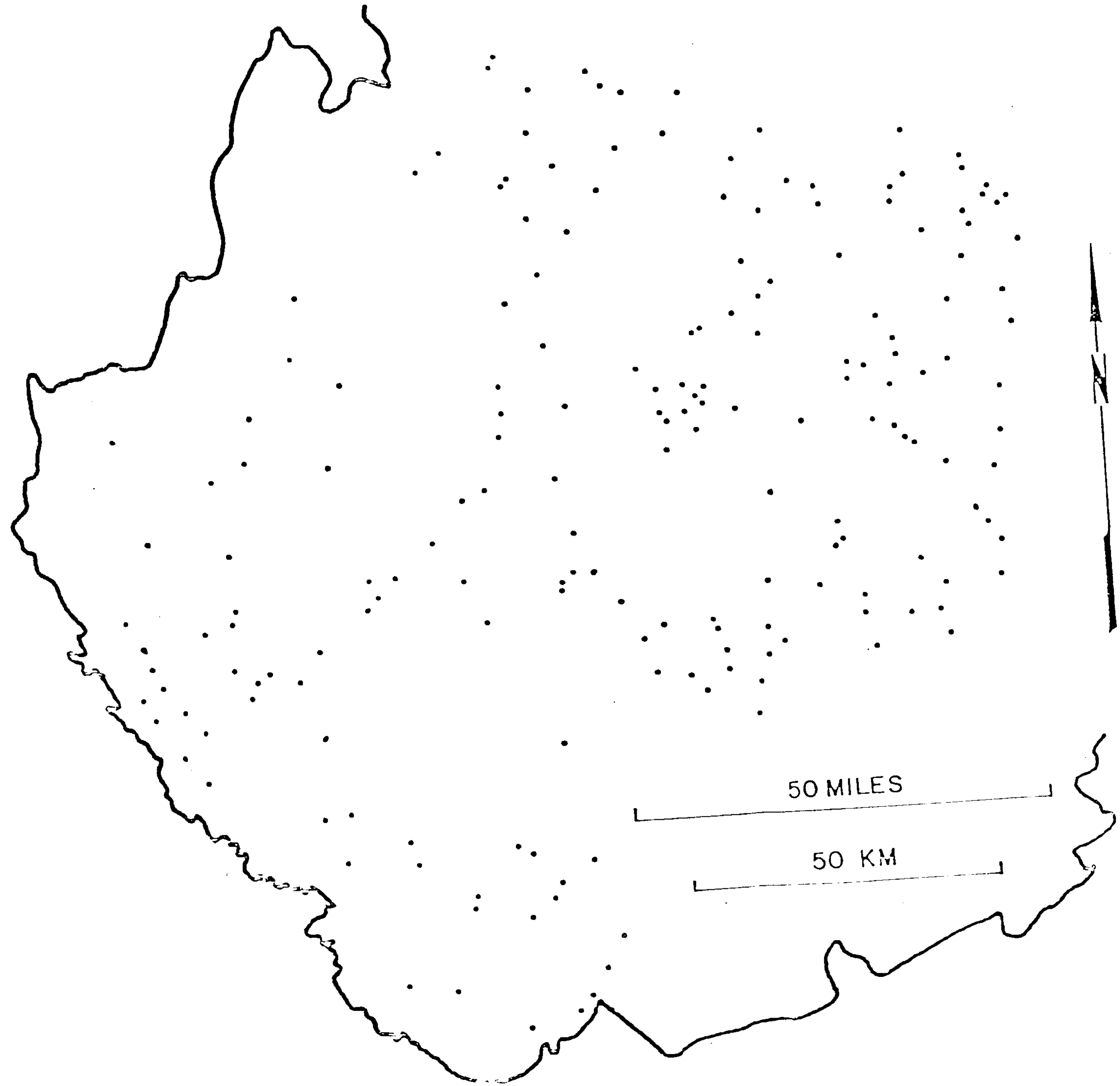

Figure 23. Points of structural change in southwestern West Virginia. Shown are points where surface structures terminate or abruptly change height or direction.

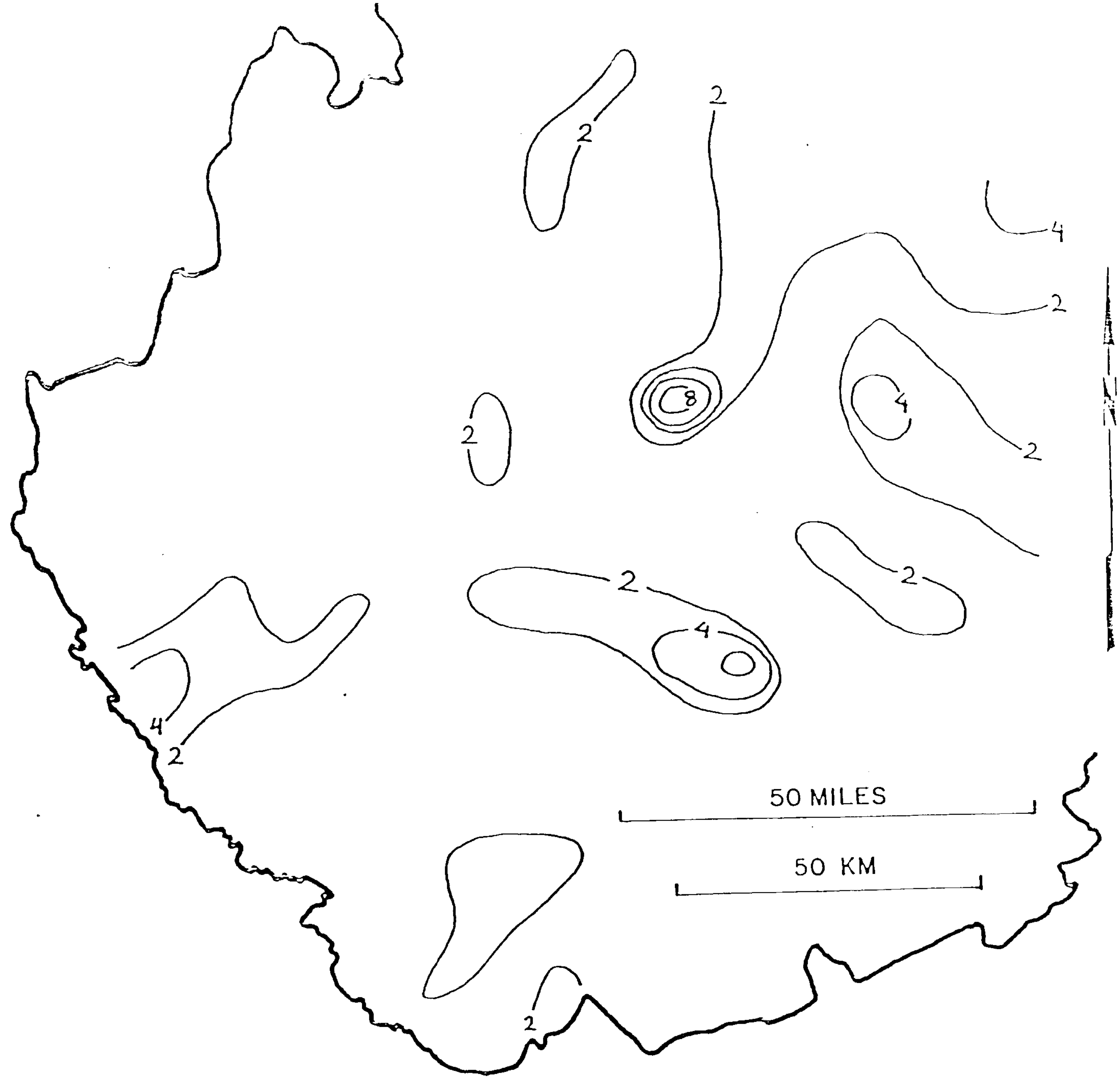

Figure 24. Density contour map of the points shown in figure 23. Contour values are the number of points in an area of about 64 mi^2 (200 km^2).

test shows that the actual is significantly greater than expected with $\alpha < 0.001$.

Thus, in the Appalachian Plateau of southern West Virginia, there is an association between structural points and photolineaments. Also, the 38th Parallel Lineament is a zone of increased density of structural points.

Geophysical Relationships: In order to check the hypothesis that the 38th Parallel Lineament is related to basement features, aeromagnetic maps were consulted. From the data available on open file maps of the West Virginia Geological and Economic Survey (1974a,b) a map of axes of magnetic highs and lows was produced (figure 25). The axes were drawn on the aeromagnetic contour maps treating them in the same manner as geological structure contour maps. The resulting map shows a change in pattern across the 38th Parallel Lineament. The magnetic axes of the northern portion of this map are regular and generally parallel to each other. To the south, on the other hand, there is little pattern. The axes are in various directions and many are quite short. This could be indicative of two basement blocks of different origins whose common boundary falls along the 38th Parallel Lineament. However, some caution is required in the interpretation of this data. The difference may be an artifact since two different aeromagnetic surveys are involved and their juncture is near the boundary in question. Although it is unlikely to have such a pronounced difference due to different surveys, particularly since both surveys were done in the same manner, it is still possible.

Stratigraphic Relations: In any analysis of structures it is often instructive to check variations in stratigraphy along regional strike. There may be changes in thickness and/or lithology which can be used to unravel the structural history of the area. Along the 38th Parallel Lineament in West Virginia, stratigraphic evidence indicates some type of activity during at least the Devonian and Mississippian and probably into the Pennsylvanian.

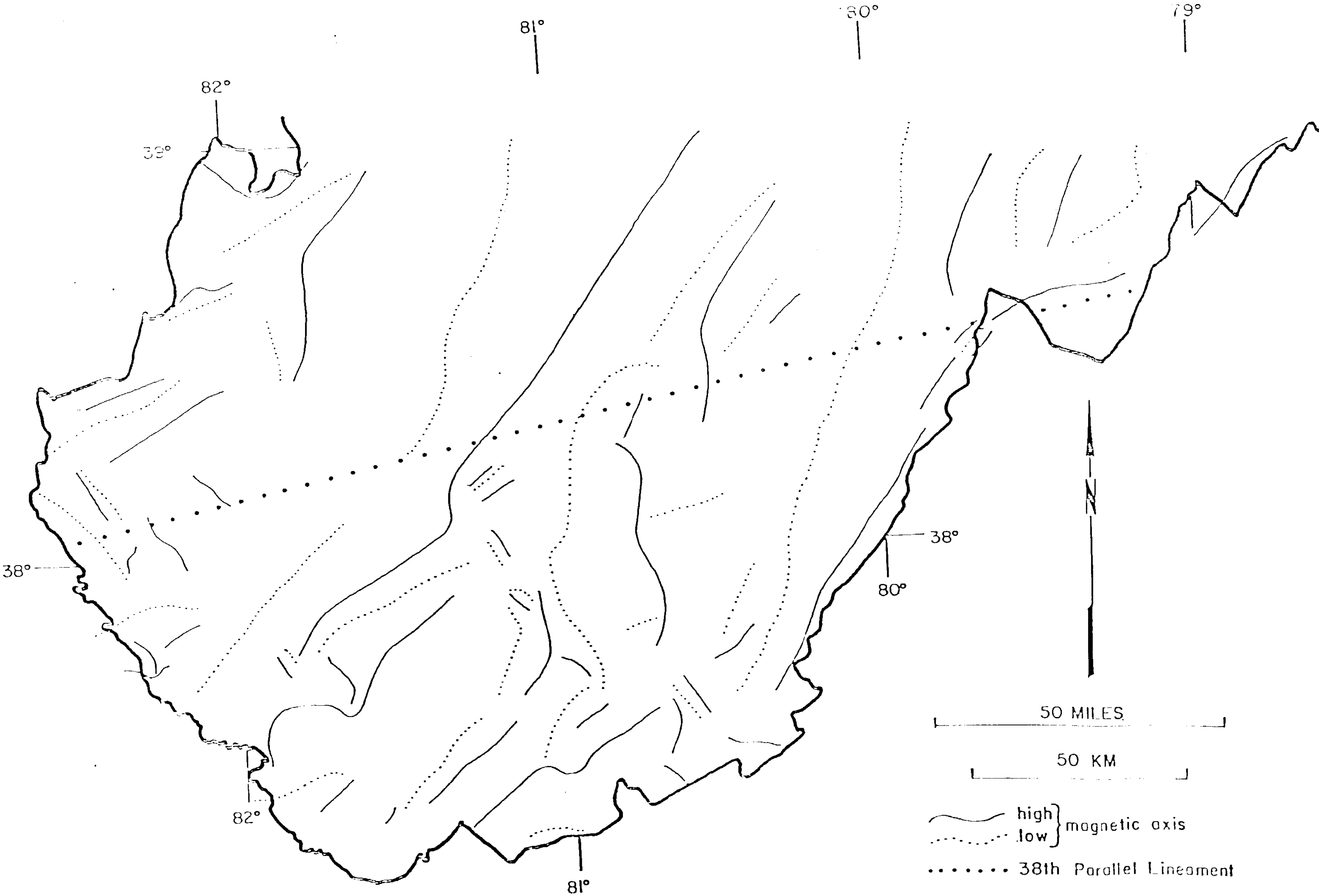

Figure 25. Magnetic axes in the southern two-thirds of West Virginia.

The map of thickness of Devonian rocks (de Witt et al., 1975) shows a rather narrow belt of thinning along the course of the Lineament, particularly in eastern West Virginia where the rocks are up to 300 m thinner than expected from the regional pattern. For the Mississippian, the map of de Witt (1975) shows a relatively uniform thickness of rocks north of the Lineament and a rather abrupt thickening south of the Lineament from about 300m to about 1500m.

In addition to the general thickness variations, individual formations and members of formations show considerable variation in thickness and lithology in the vicinity of the Lineament. For example, the lower formations in the Mississippian Greenbrier Group disappear within the 38th Parallel Lineament zone in outcrop in eastern West Virginia. The remaining formations thin and some change character in this same area. Williamson's (1974) investigation of the Mississippian Pocono Formation in southern West Virginia shows that many facies and thickness changes occur in several members across the Lineament.

Miscellaneous Observations: Several other observations of a qualitative or preliminary nature have been made in connection with either the prominent photolineaments or the 38th Parallel Lineament zone. Some of these are of interest to the present study and will be presented here.

Observations on distribution patterns of joint azimuths indicate that joints from single outcrops are less related to the overall pattern of photolineaments than to a single nearby photolineament (for some examples, see Werner, 1975a). This would imply that surface joint patterns are much more affected by local conditions than those of a scale comparable to the 38th Parallel Lineament zone. Hence any investigation of the relation of surface fractures to the 38th Parallel Lineament would require measurement of more than azimuth of joints.

Joint spacing seems to be less everywhere within the Lineament zone than elsewhere. Most of these observations so far are of a qualitative nature; however, some measurements have been made on the limestones of the Greenbrier Group. At several localities well to the north of the 38th Parallel Lineament zone, and also off any other prominent lineaments, spacing is on the order of 10m. Within the Lineament zone, spacing is on the order of 1m. South of the Lineament, there is probably interference due to the interaction of the forces responsible for the Central and the Southern Appalachians; the junction of the two geologic provinces is close to localities measured. At these localities, spacing of fractures tends to be somewhat greater than 1m, but not very much. These measurements hold true only for the rather massive limestone beds of the Greenbrier, other lithologies yield entirely different measurements.

Many small faults in competent beds and contortions in incompetent beds have been observed at or near prominent photolineaments within the 38th Parallel Lineament zone; however, it remains for future work to determine whether or not there is an association here and what type of association there may be.

Some earthquakes have been observed along the 38th Parallel Lineament zone; however, relatively poor location information has prevented any statistical analysis of their distribution.

Chapter 3 HYDROCARBONS AND THEIR RELATIONSHIP TO PHOTOLINEAMENTS AND FRACTURES

Section 1 Natural Gas Production from Devonian Shale in West Virginia

Natural gas is produced from the Devonian shales in most of the southwestern counties of West Virginia (figure 7.). Two small areas were selected for a test of the various relationships between production and photolineaments. Area 1 is Wayne County, which is astride the West Virginia extension of the 38th Parallel Lineament; area 2 is Jackson and Mason counties and includes the area of the Cottageville (Mt. Alto) gas field.

The production data used was derived from drillers' logs on file with the West Virginia Geological and Economic Survey. This data has some problems characteristic of such logs. Data is quite variable in quality. Some drillers are apparently more careful and knowledgeable than others. This is clearly shown by the amount of detail in the log. Also, some companies always show the initial production data, some never do, and some show it only occasionally. It was not always totally certain that the gas reported came from the Devonian shale and only the shale. Although care was taken to eliminate all production values which included other pay zones, some such may be included in the data used. It is also possible that some wells reported as dry holes in the shale may not actually be so. The shale may have been ignored entirely and no attempt made to produce it. Another difficulty arises for the after-stimulation production values. The time period between the stimulation shot and the production test varied considerably, and may have been as little as three hours or as great as ninety-six hours. No one time period was common to all, so the last report was the one used.

Location data sometimes was also uncertain. All locations were obtained directly from the driller's log. There were some discrepancies evident between these and some publications giving well location (e.g., Overbey, 1961), however, these are very few. Table 1 lists data for three hundred and ninety gas wells which have some production information given on the drillers' logs. Of these wells, the locations for five could not be determined. The data for the remaining three hundred and eighty-five is portrayed on figure 26 and plates 2 - 5.

Table 2 lists data for one hundred and nine gas wells of Jackson and Mason counties which have some Devonian shale gas production information. Locations were not determined for fourteen of these and the remaining one hundred and forty-five are graphically shown on figure 27 and plates 6 - 9. As can be clearly seen, most of the information on Devonian shale gas for this area comes from the Cottageville gas field. Clearly also, the Cottageville field is unusual as far as production rates are concerned. The symbols on figure 26 are scaled at one-half the size of these on figure 25. It is thus obvious that the final open flow rates of the Cottageville field are significantly greater than those of the other areas shown in this report.

Section 2 Relationship between Gas Production and Proximity to Photolineaments

Test analyses were done for Wayne County and for the Jackson-Mason County area. The photolineament maps for both areas (figures 26 and 27) were prepared in a similar manner. Individual maps were produced for each of the types of imagery available (8 maps for Jackson-Mason, 4 maps for Wayne). These were then superimposed and those photolineaments which appeared on two or more maps were extracted and are shown on figures 26 and 27. Superimposed on these photolineament maps are the before- and after-shot flow data.

The results for Wayne County seem to indicate that the natural open flows are less on or near photolineaments. After-shot open flows are not clearly related to photolineaments. Although some of the wells with high after-shot

Table 1. (pages 66-71) Devonian shale gas production data for Wayne County, West Virginia. Approximately one-half of the logs deposited with the West Virginia Geological and Economic Survey were inspected.

N_COORD - north coordinate in 100's of meters on the Universal Transverse Mercator grid, zone 17.

E_COORD - east coordinate in 100's of meters on the Universal Transverse Marcator grid, zone 17.

ELEV - elevation of well top in feet above sea level.

GAS - gas show measured in MCF/day. This is generally the last (and highest) within the Devonian shale.

NATURAL - natural open flow in MCF/day.

AFT_SHOT - last measured open flow after stimulation in MCF/day.

A period in any data position indicates no information available.

UGR File #40
W.Va.Univ.Dep. of Geology and Geography
Dec. 1977

DATA FOR GAS WELLS IN WAYNE COUNTY

WELL_NO	N_COORD	E_COORD	ELEV	GAS	NATURAL	AFT_SHOT
WAY- 19	42178.0	3774.0	1291.0	3.80	1.30	77.00
WAY- 37	42011.0	3847.0	793.1	59.00	60.00	133.00
WAY- 43	42182.0	3807.0	1018.0	6.70	6.70	79.00
WAY- 89	42380.0	3719.0	608.9	17.00	.	.
WAY- 91	.	.	596.0	60.00	.	.
WAY- 92	.	.	770.0	.	.	23.00
WAY- 95	42403.0	3854.0	610.0	.	17.00	95.00
WAY- 97	.	.	710.0	.	.	765.00
WAY- 98	.	.	.	41.00	.	.
WAY- 101	42030.0	3706.0	858.0	21.00	.	.
WAY- 105	42306.0	3805.0	730.4	.	.	1165.00
WAY- 106	42408.0	3864.0	990.0	.	.	320.00
WAY- 108	42407.0	3851.0	712.9	.	.	106.00
WAY- 109	42299.0	3774.5	.	.	.	.
WAY- 111	42406.0	3848.0	619.0	.	1847.00	.
WAY- 112	42321.0	3783.0	871.4	.	.	179.00
WAY- 113	42402.0	3846.0	650.0	.	.	17.00
WAY- 114	42270.0	3637.0	746.5	.	.	319.00
WAY- 115	41907.0	3755.0	607.0	.	.	82.00
WAY- 119	42306.0	3758.0	765.0	.	.	521.28
WAY- 120	42308.0	3787.0	1051.0	.	.	218.00
WAY- 122	42471.0	3668.0	643.6	.	.	59.00
WAY- 123	42397.0	3848.0	845.0	.	.	38.00
WAY- 129	42300.0	3780.0	907.9	7.00	.	210.00
WAY- 132	42320.0	3796.0	679.3	.	.	273.00
WAY- 133	42493.0	3719.0	615.0	.	.	312.00
WAY- 135	.	.	917.0	.	.	200.00
WAY- 136	42372.0	3794.0	590.0	26.00	.	556.00
WAY- 137	42288.0	3765.0	1054.0	22.00	.	231.00
WAY- 147	42149.0	3742.0	664.3	0.00	0.00	0.00
WAY- 148	42496.0	3641.0	523.3	.	.	26.00
WAY- 149	42327.0	3794.0	820.0	.	.	146.00
WAY- 150	42320.0	3791.0	675.0	.	.	900.00
WAY- 151	42334.0	3800.0	625.0	.	.	60.00
WAY- 157	42308.0	3707.0	820.0	6.00	.	73.00
WAY- 164	42466.0	3667.0	850.0	0.00	0.00	0.00
WAY- 165	42315.0	3802.0	950.0	850.00	.	.
WAY- 168	42304.0	3792.0	930.0	84.00	.	440.00
WAY- 169	42293.0	3790.0	875.0	84.00	.	135.00
WAY- 171	42283.0	3782.0	850.0	.	.	84.00
WAY- 172	42263.0	3789.0	875.0	43.00	.	60.00
WAY- 173	42337.0	3743.0	796.2	5.00	.	281.00
WAY- 174	42287.0	3821.0	426.0	21.00	.	60.00
WAY- 179	42361.0	3844.0	725.0	.	.	95.00
WAY- 181	42288.0	3810.0	858.4	.	.	94.00
WAY- 183	42377.0	3709.0	858.4	.	.	94.00
WAY- 184	42264.0	3777.0	616.0	21.00	.	84.00
WAY- 185	42315.0	3790.0	703.0	.	.	300.00
WAY- 186	42358.0	3722.0	624.0	.	-10.00	60.00
WAY- 187	42302.0	3823.0	780.0	.	18.30	103.00
WAY- 188	42325.0	3788.0	724.0	.	.	497.00
WAY- 192	42281.0	3798.0	820.0	.	.	60.00
WAY- 193	42044.0	3811.0	731.0	4918.00	.	582.00
WAY- 195	42473.0	3718.0	971.7	.	.	18.00
WAY- 196	42478.0	3714.0	988.1	.	.	60.00
WAY- 197	42312.0	3789.0	670.0	150.00	.	.
WAY- 199	42335.0	3711.0	755.0	0.00	0.00	0.00
WAY- 200	42082.0	3705.0	743.8	15.00	.	.
WAY- 201	42336.0	3733.0	810.0	0.00	0.00	0.00
WAY- 202	42325.0	3756.0	600.0	0.00	0.00	0.00
WAY- 203	42296.0	3803.0	805.0	.	.	146.00
WAY- 204	42300.0	3760.0	748.0	0.00	.	327.00
WAY- 207	42313.0	3809.0	1040.0	.	42.00	340.00
WAY- 208	42323.0	3812.0	975.0	.	.	105.00
WAY- 209	42486.0	3711.0	823.9	.	.	73.00
WAY- 210	42051.0	3808.0	733.0	21.00	.	71.00
WAY- 212	42344.0	3744.0	580.0	.	305.00	.
WAY- 213	41908.0	3762.0	890.0	925.00	.	450.00
WAY- 216	42326.0	3791.0	800.0	.	.	67.00
WAY- 220	42037.0	3810.0	729.3	0.00	0.00	0.00
WAY- 221	42291.0	3762.0	1000.0	.	.	103.00
WAY- 223	42343.0	3742.0	545.2	.	.	84.00

W.Va.Univ.Dept. of Geology and Geography
Dec. 1977

DATA FOR GAS WELLS IN WAYNE COUNTY

WELL_NO	N_COORD	E_COORD	ELEV	GAS	NATURAL	AFT_SHOT
WAY- 224	42334.0	3823.0	765.0	.	.	227.00
WAY- 226	42327.0	3743.0	679.0	.	.	94.08
WAY- 227	42341.0	3821.0	1040.0	0.00	0.00	0.00
WAY- 229	42345.0	3749.0	591.0	35.00	.	169.00
WAY- 230	42049.0	3799.0	720.0	0.00	.	43.00
WAY- 232	42337.0	3755.0	599.9	.	.	231.00
WAY- 233	42305.0	3760.0	669.0	105.00	.	444.00
WAY- 234	42333.0	3747.0	775.0	0.00	.	175.00
WAY- 236	42088.0	3705.0	646.0	16.73	.	113.00
WAY- 238	42334.0	3812.0	650.0	.	.	60.00
WAY- 239	42236.0	3817.0	690.0	.	.	34.00
WAY- 240	42309.0	3792.0	792.8	.	0.00	55.00
WAY- 241	42335.0	3751.0	614.0	.	.	48.00
WAY- 242	42155.0	3749.0	796.0	0.00	.	94.00
WAY- 243	42348.0	3753.0	790.0	2.20	.	0.00
WAY- 244	42302.0	3766.0	892.6	.	.	298.00
WAY- 245	42291.0	3773.0	903.6	14.00	.	178.00
WAY- 247	42027.0	3806.0	762.0	89.00	.	129.00
WAY- 251	42348.0	3743.0	603.6	1.68	.	166.00
WAY- 254	42181.0	3731.0	907.0	.	.	20.00
WAY- 255	42291.0	3783.0	969.5	10.00	.	.
WAY- 256	42314.0	3761.0	774.0	.	.	115.96
WAY- 257	42362.0	3754.0	720.0	0.00	.	75.00
WAY- 258	42359.0	3759.0	707.0	16.00	.	71.00
WAY- 259	42312.0	3764.0	927.0	.	.	30.00
WAY- 260	42014.0	3806.0	1257.0	79.00	.	133.00
WAY- 261	42305.0	3819.0	931.0	6.00	.	113.00
WAY- 262	42375.0	3715.0	751.0	19.00	.	73.00
WAY- 265	42391.0	3740.0	694.2	25.00	.	79.00
WAY- 266	42320.0	3818.0	693.3	4.00	.	206.00
WAY- 268	42409.0	3734.0	574.0	.	.	60.00
WAY- 269	42177.0	3820.0	816.0	3.00	.	39.00
WAY- 270	42384.0	3704.0	799.1	0.00	.	.
WAY- 275	41977.0	3731.0	627.0	43.14	.	84.00
WAY- 277	42369.0	3655.0	608.2	0.00	0.00	0.00
WAY- 279	42245.0	3800.0	621.2	17.00	0.00	0.00
WAY- 284	42408.0	3755.0	569.5	25.00	.	.
WAY- 285	42135.0	3926.0	937.1	47.00	.	222.00
WAY- 286	42009.0	3756.0	850.8	.	1107.00	.
WAY- 288	42333.0	3781.0	720.0	.	.	10.00
WAY- 289	42146.0	3916.0	1093.5	0.00	.	119.00
WAY- 291	42136.0	3914.0	1055.1	.	.	157.00
WAY- 301	42002.0	3719.0	923.0	42.00	84.00	94.00
WAY- 309	42307.0	3743.0	596.0	2.50	.	290.00
WAY- 310	42011.0	3760.0	1165.9	.	.	60.00
WAY- 313	42175.0	3768.0	739.3	0.00	0.00	0.00
WAY- 325	42012.0	3769.0	822.6	.	.	84.00
WAY- 328	42047.0	3823.0	860.7	1168.00	1044.00	.
WAY- 331	42299.0	3740.0	835.2	11.50	.	240.00
WAY- 337	42291.0	3638.0	668.7	0.00	0.00	0.00
WAY- 339	42019.0	3763.0	880.6	.	.	103.00
WAY- 340	42063.0	3832.0	1135.8	39.00	43.00	601.00
WAY- 341	42069.0	3833.0	1008.5	.	7.00	40.00
WAY- 342	42071.0	3829.0	1087.6	.	0.50	24.00
WAY- 344	41917.0	3703.0	720.9	.	.	189.00
WAY- 345	42316.0	3838.0	725.0	.	.	146.00
WAY- 346	42219.0	3765.0	637.4	0.49	0.00	0.00
WAY- 347	42054.0	3813.0	758.5	.	9.00	166.00
WAY- 348	42208.0	3840.0	1050.0	.	0.00	36.00
WAY- 349	42301.0	3748.0	1057.1	.	9.00	71.00
WAY- 350	42317.0	3826.0	915.6	0.35	0.12	59.00
WAY- 358	42307.0	3753.0	1025.5	2.68	10.00	100.00
WAY- 359	42166.0	3854.0	604.2	1.83	1.70	147.00
WAY- 382	42040.0	3819.0	1039.1	71.00	.	266.00
WAY- 383	42100.0	3696.0	653.5	18.37	16.20	42.00
WAY- 393	42324.0	3641.0	759.6	0.00	0.00	0.00
WAY- 396	42076.0	3710.0	1041.5	12.00	13.00	631.00
WAY- 397	42044.0	3835.0	1156.7	27.00	22.00	208.00
WAY- 398	42319.0	3748.0	924.3	3.97	3.00	33.00
WAY- 399	42211.0	3549.0	592.0	0.00	0.00	0.00
WAY- 403	42315.0	3815.0	800.0	29.80	29.80	210.00
WAY- 407	42073.0	3714.0	1003.2	8.10	7.00	71.00

DATA FOR GAS WELLS IN WAYNE COUNTY

WELL_NO	N_COORD	E_COORD	ELEV	GAS	NATURAL	AFT_SHOT
WAY- 408	42094.0	3690.0	1097.5	15.40	15.00	40.00
WAY- 409	42041.0	3820.0	1024.2	.	.	115.00
WAY- 410	42304.0	3726.0	924.3	0.46	.	147.00
WAY- 411	42123.0	3666.0	657.8	19.00	17.00	46.00
WAY- 412	42311.0	3686.0	1020.0	0.00	0.00	0.00
WAY- 414	42123.0	3887.0	976.1	.	0.27	83.00
WAY- 415	42309.0	3823.0	755.0	60.00	.	169.00
WAY- 416	42070.5	3719.5	.	.	.	.
WAY- 417	42160.0	3854.0	1081.6	0.00	6.00	196.00
WAY- 419	42162.0	3844.0	659.6	47.67	.	886.00
WAY- 425	42368.0	3722.0	590.0	.	.	94.00
WAY- 426	42081.0	3711.0	1036.0	.	0.00	38.00
WAY- 431	42358.0	3847.0	675.0	.	.	125.00
WAY- 432	42170.0	3856.0	.	.	.	84.00
WAY- 433	42162.0	3849.0	.	.	11.85	86.00
WAY- 434	42025.0	3836.0	973.6	.	77.00	113.00
WAY- 436	42163.0	3842.0	675.0	.	.	375.00
WAY- 439	42158.0	3842.0	739.3	.	.	226.00
WAY- 441	41992.0	3816.0	1400.0	.	14.90	258.73
WAY- 442	42101.0	3873.0	873.9	.	299.00	499.00
WAY- 452	42104.0	3882.0	690.0	.	66.66	.
WAY- 473	42140.0	3811.0	982.0	18.00	.	239.00
WAY- 474	42167.0	3807.0	746.8	.	0.00	179.00
WAY- 478	42154.0	3824.0	949.3	.	0.00	146.00
WAY- 480	42160.0	3835.0	743.9	.	0.00	189.00
WAY- 484	42167.0	3843.0	857.0	.	0.98	43.00
WAY- 486	42104.0	3867.0	999.1	.	0.39	177.00
WAY- 487	42045.0	3827.0	1014.2	.	37.00	230.00
WAY- 489	42405.0	3827.0	605.0	14.90	.	141.00
WAY- 490	42066.0	3827.0	1022.3	.	114.00	834.00
WAY- 491	42332.0	3831.0	970.0	.	.	84.00
WAY- 493	42390.0	3835.0	762.0	.	.	398.00
WAY- 495	42151.0	3874.0	1142.7	.	160.00	896.00
WAY- 498	42032.0	3841.0	1294.4	.	45.00	235.00
WAY- 502	42173.0	3864.5	724.0	37.00	21.00	133.00
WAY- 503	42168.5	3870.5	740.0	.	0.00	133.00
WAY- 504	42165.0	3829.0	851.0	15.00	15.00	52.00
WAY- 505	42401.0	3835.0	600.0	.	.	250.00
WAY- 507	42177.5	3875.0	1118.0	103.00	103.00	337.00
WAY- 508	42385.5	3839.0	599.0	.	.	134.00
WAY- 509	42174.5	3803.5	890.0	.	0.00	21.00
WAY- 510	42153.5	3874.0	1027.0	57.00	54.00	366.00
WAY- 512	42074.5	3832.0	820.0	1961.00	539.00	540.00
WAY- 513	42073.0	3827.0	843.0	.	0.00	146.00
WAY- 515	42154.5	3839.0	1103.0	152.00	140.00	273.00
WAY- 518	42146.5	3871.5	1084.0	45.00	60.00	280.00
WAY- 519	42160.5	3839.5	707.0	4.97	4.41	188.00
WAY- 520	42147.5	3889.0	.	.	.	.
WAY- 521	42146.0	3884.5	897.0	.	.	950.00
WAY- 522	42149.0	3866.5	1059.0	60.00	57.00	133.00
WAY- 523	41971.0	3756.0	711.0	.	.	242.00
WAY- 524	42148.5	3859.5	950.0	47.00	47.00	146.00
WAY- 526	41950.0	3786.0	1165.0	18.00	18.00	140.00
WAY- 529	42071.5	3816.0	1247.0	36.00	60.00	133.00
WAY- 530	42155.0	3886.0	1141.0	.	.	1000.00
WAY- 533	42160.0	3875.5	821.0	103.00	103.00	539.00
WAY- 534	42157.0	3734.0	1128.0	.	21.00	94.00
WAY- 535	42169.0	3734.5	729.0	58.00	45.00	421.00
WAY- 536	42177.5	3888.0	1001.0	18.00	18.00	127.00
WAY- 537	42173.0	3877.0	1017.0	18.00	18.00	223.00
WAY- 539	42152.5	3831.0	859.0	.	.	275.00
WAY- 541	42371.5	3914.5	675.0	.	.	745.00
WAY- 542	42217.0	3861.0	963.0	12.00	21.00	140.00
WAY- 543	42209.5	3864.0	1028.0	.	.	30.00
WAY- 544	42128.5	3801.5	989.0	.	0.00	56.00
WAY- 546	42152.0	3880.5	1009.0	51.40	54.00	360.00
WAY- 547	42137.0	3731.0	909.0	.	18.00	73.00
WAY- 548	42393.0	3839.0	619.0	.	0.00	73.00
WAY- 552	42169.0	3890.5	1000.0	.	.	900.00
WAY- 553	42168.5	3833.0	662.0	119.00	60.00	103.00
WAY- 555	41945.5	3794.0	985.0	.	.	267.00
WAY- 556	42011.0	3785.0	765.0	.	.	1100.00

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DATA FOR GAS WELLS IN WAYNE COUNTY

WELL_NO	N_COORD	E_COORD	ELEV	GAS	NATURAL	AFT_SHOT
WAY- 557	42026.5	3795.0	1275.0	.	.	84.00
WAY- 558	42002.0	3780.5	960.0	.	119.00	.
WAY- 559	42149.0	3910.0	1004.0	.	14.90	103.00
WAY- 560	42157.0	3814.0	1229.0	.	.	43.00
WAY- 561	42007.0	3787.5	1229.0	8.50	7.70	140.00
WAY- 562	42402.5	3834.5	597.0	.	.	426.00
WAY- 567	42069.5	3840.5	800.0	15.00	11.00	179.00
WAY- 568	42008.0	3791.5	1327.0	.	.	3.60
WAY- 569	42224.5	3847.0	810.0	30.00	30.00	68.00
WAY- 570	42220.0	3853.5	1021.0	.	0.00	127.00
WAY- 571	42017.0	3840.5	1451.0	27.00	25.00	154.00
WAY- 573	42124.5	3810.5	1209.0	152.00	133.00	198.00
WAY- 574	42120.5	3841.5	1060.0	.	39.00	84.00
WAY- 575	42129.0	3840.5	1253.0	.	0.00	24.00
WAY- 577	42129.0	3821.0	1084.0	.	1245.00	.
WAY- 578	42053.0	3754.5	776.0	28.00	21.00	54.00
WAY- 581	42175.5	3892.5	1047.0	33.00	33.00	189.00
WAY- 582	42067.0	3846.5	1029.0	76.00	76.00	231.00
WAY- 583	42050.5	3836.0	1276.0	.	4.00	60.00
WAY- 588	41993.0	3784.5	950.0	.	.	53.00
WAY- 590	42174.5	3828.0	609.0	.	0.00	33.00
WAY- 591	42200.0	3867.5	1063.0	.	0.00	73.00
WAY- 594	41938.5	3784.5	1086.0	.	0.00	52.00
WAY- 595	42139.0	3869.0	1026.0	.	0.00	60.00
WAY- 597	42134.0	3880.5	675.0	140.00	119.00	140.00
WAY- 598	42012.5	3791.0	832.0	208.00	240.00	210.00
WAY- 599	42139.0	3886.5	1097.0	.	0.00	26.00
WAY- 600	42133.0	3874.0	797.0	.	0.00	49.00
WAY- 601	42139.5	3860.0	699.0	.	0.00	58.00
WAY- 602	42407.5	3837.5	620.0	.	.	281.00
WAY- 603	42364.0	3809.5	546.0	.	.	800.00
WAY- 608	41957.5	3774.5	738.0	353.00	353.00	438.00
WAY- 609	42368.5	3812.5	591.0	.	0.00	223.00
WAY- 611	42129.0	3846.0	914.0	129.00	.	282.00
WAY- 614	42154.0	3896.0	.	.	.	.
WAY- 616	42160.0	3896.0	1079.0	33.00	0.00	28.00
WAY- 617	42063.0	3761.5	904.0	1961.00	381.00	440.00
WAY- 618	42081.5	3824.0	1057.0	.	0.00	30.00
WAY- 619	42370.0	3802.0	595.0	.	.	205.00
WAY- 620	41994.5	3779.0	1293.0	.	0.00	127.00
WAY- 621	42183.0	3891.5	1030.0	.	119.00	.
WAY- 622	42363.0	3834.0	1029.0	.	0.00	50.00
WAY- 623	42062.0	3768.5	862.0	84.00	60.00	321.00
WAY- 624	42068.5	3758.5	786.0	.	60.00	84.00
WAY- 625	42082.0	3830.0	1111.0	.	.	14.00
WAY- 626	42080.0	3835.5	1060.0	.	0.00	21.00
WAY- 627	42115.5	3799.5	1194.0	11.00	11.00	15.00
WAY- 628	42123.5	3797.5	1090.0	.	0.00	28.00
WAY- 631	42142.0	3800.0	1000.0	.	0.00	25.80
WAY- 632	42229.5	3858.0	887.0	.	0.00	94.00
WAY- 633	42055.5	3831.5	1020.0	18.00	16.00	113.00
WAY- 634	42029.5	3837.0	1122.0	.	31.00	121.00
WAY- 635	41998.0	3796.5	889.0	.	0.00	45.00
WAY- 636	41988.5	3791.0	994.0	.	0.00	84.00
WAY- 637	42014.0	3847.0	919.0	.	0.00	73.00
WAY- 638	42370.0	3790.5	750.0	.	.	119.00
WAY- 639	42368.5	3816.0	760.0	.	119.00	377.00
WAY- 640	42372.0	3820.0	926.0	.	0.00	206.00
WAY- 641	42064.5	3771.5	941.0	.	89.00	1073.00
WAY- 642	42375.5	3819.0	795.0	21.00	15.00	286.00
WAY- 643	42280.0	3706.0	611.0	41.00	38.00	262.00
WAY- 644	42292.0	3737.5	615.0	5.00	6.50	64.00
WAY- 645	42367.5	3804.0	564.0	21.00	0.00	152.00
WAY- 646	42359.5	3807.5	726.0	.	21.00	202.00
WAY- 647	42362.0	3813.0	613.0	33.00	33.00	146.00
WAY- 648	42016.5	3856.0	1250.0	.	.	150.00
WAY- 650	42149.5	3842.5	795.0	94.00	84.00	179.00
WAY- 651	42143.5	3844.0	912.0	94.00	73.00	158.00
WAY- 652	42139.0	3841.0	1093.0	54.00	54.00	112.00
WAY- 653	42132.5	3839.5	1243.0	.	33.00	94.00
WAY- 654	42133.0	3837.5	.	.	.	.
WAY- 655	42375.0	3813.0	679.0	.	0.00	133.00

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DATA FOR GAS WELLS IN WAYNE COUNTY

WELL_NO	N_COORD	E_COORD	ELEV	GAS	NATURAL	AFT_SHOT
WAY- 656	42165.0	3897.0	847.0	26.00	21.00	84.00
WAY- 657	42135.0	3933.0	917.0	.	1043.00	.
WAY- 658	42146.0	3951.0	906.0	.	.	60.00
WAY- 661	42346.0	3787.0	949.0	.	0.00	109.00
WAY- 663	42133.5	3864.0	690.0	.	0.00	253.00
WAY- 664	42194.5	3881.0	1086.0	.	30.00	84.00
WAY- 665	42161.0	3903.5	1031.0	15.00	0.00	158.00
WAY- 666	42154.0	3905.0	1083.0	15.00	15.00	146.00
WAY- 667	42071.0	3769.0	1111.0	24.00	21.00	184.00
WAY- 668	42252.5	3804.0	757.0	.	60.00	103.00
WAY- 669	42170.5	3895.0	1149.0	84.00	60.00	133.00
WAY- 671	42030.0	3835.0	1245.0	21.00	21.00	42.00
WAY- 672	42359.5	3793.0	803.0	169.00	103.00	146.00
WAY- 673	42382.5	3831.5	650.0	290.00	189.00	340.00
WAY- 674	42401.0	3862.0	1029.0	21.00	15.00	223.00
WAY- 675	42071.0	3859.5	1053.0	207.00	198.00	298.00
WAY- 676	42380.5	3815.5	968.0	.	0.00	127.00
WAY- 677	42366.0	3784.0	670.0	.	.	176.00
WAY- 678	42406.0	3827.0	599.0	.	.	200.00
WAY- 679	42134.0	3920.0	952.0	823.00	291.00	264.00
WAY- 682	42368.5	3818.5	730.0	.	18.20	133.00
WAY- 684	42363.0	3809.5	598.0	.	.	189.00
WAY- 685	42379.5	3824.5	902.0	.	.	705.00
WAY- 687	42416.0	3840.5	682.0	.	.	100.00
WAY- 688	42435.5	3725.0	565.0	.	.	103.00
WAY- 690	42132.5	3934.5	1219.0	60.00	49.00	304.00
WAY- 691	42401.0	3830.0	710.0	.	.	125.00
WAY- 692	42342.5	3756.5	595.0	.	21.00	119.00
WAY- 693	42431.5	3728.5	550.0	.	.	73.00
WAY- 696	42424.0	3845.5	787.0	.	.	146.00
WAY- 698	42381.5	3824.0	908.0	.	.	41.30
WAY- 702	42428.5	3725.5	620.0	.	.	50.00
WAY- 704	42348.0	3757.0	680.0	.	0.00	70.00
WAY- 709	42378.0	3828.0	852.0	.	.	57.00
WAY- 710	41967.0	3722.0	723.0	133.00	127.00	158.00
WAY- 712	42072.0	3704.0	1107.0	239.00	223.00	880.00
WAY- 713	42063.0	3774.0	813.0	15.00	21.00	60.00
WAY- 714	42127.5	3876.5	959.0	60.00	133.00	163.00
WAY- 715	42114.5	3878.5	1120.0	.	15.00	60.00
WAY- 718	42378.5	3822.5	913.0	.	.	497.00
WAY- 722	42347.0	3769.5	725.0	.	.	133.00
WAY- 723	42024.5	3799.0	974.0	22.00	21.00	83.00
WAY- 724	42362.0	3794.0	810.0	.	.	106.00
WAY- 726	41973.5	3788.5	1038.0	21.00	11.00	103.00
WAY- 727	41970.0	3814.0	1311.0	.	0.00	127.00
WAY- 728	42028.0	3783.0	1169.0	.	0.00	94.00
WAY- 729	42135.5	3845.5	989.0	.	0.00	45.00
WAY- 730	42107.0	3873.0	956.0	.	0.00	60.00
WAY- 732	42102.0	3864.5	1050.0	.	0.00	119.00
WAY- 734	41963.5	3769.5	826.0	.	0.00	84.00
WAY- 735	41965.5	3783.0	896.0	.	0.00	103.00
WAY- 737	41997.0	3818.5	843.0	0.50	0.50	81.00
WAY- 738	42133.0	3839.5	956.0	.	0.00	47.00
WAY- 739	42131.5	3847.5	1079.0	15.00	11.00	119.00
WAY- 741	42344.0	3773.0	755.0	.	.	146.00
WAY- 744	42099.0	3869.5	878.0	.	0.00	38.00
WAY- 746	42035.0	3790.0	746.0	.	.	36.00
WAY- 747	41936.0	3760.0	688.0	.	0.00	119.00
WAY- 748	42131.0	3860.0	1039.0	15.30	11.80	50.00
WAY- 749	42057.0	3770.5	694.0	24.00	24.00	189.00
WAY- 751	42074.0	3851.0	.	.	.	.
WAY- 752	42081.0	3851.0	904.0	60.00	42.00	146.00
WAY- 753	42068.0	3782.5	.	.	.	.
WAY- 754	42079.5	3843.5	1033.0	.	15.00	207.00
WAY- 756	42135.0	3823.0	1135.0	.	21.00	140.00
WAY- 758	42054.0	3826.0	1194.0	21.00	18.00	84.00
WAY- 759	42061.5	3818.5	877.0	.	0.00	112.00
WAY- 761	42059.5	3778.5	1155.0	.	15.00	61.00
WAY- 762	42060.5	3755.0	938.0	39.00	60.00	412.00
WAY- 763	42207.0	3871.5	971.0	21.00	15.00	539.00
WAY- 764	42187.5	3889.5	1097.0	33.00	26.00	146.00
WAY- 765	41948.5	3763.0	703.0	.	26.00	73.00

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DATA FOR GAS WELLS IN WAYNE COUNTY
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WELL_NO	N_COORD	E_COORD	ELEV	GAS	NATURAL	AFT_SHOT
WAY- 766	42233.5	3853.0	1081.0	.	0.00	30.00
WAY- 767	42140.5	3816.5	1149.0	.	0.00	58.00
WAY- 768	42188.5	3883.0	1011.0	179.00	146.00	267.00
WAY- 769	41994.5	3774.0	1268.0	15.00	15.00	169.00
WAY- 770	42064.4	3780.5	988.0	.	18.00	103.00
WAY- 771	42076.0	3782.5	1035.0	.	21.00	60.00
WAY- 772	42055.0	3761.0	1029.0	33.00	26.00	112.00
WAY- 775	41922.0	3771.0	743.0	.	21.00	42.00
WAY- 776	42224.0	3837.0	812.0	.	0.00	42.00
WAY- 777	42118.5	3831.0	1015.0	.	21.00	39.00
WAY- 778	41950.0	3778.5	918.0	.	0.00	32.00
WAY- 779	41927.5	3758.5	649.0	.	0.00	94.00
WAY- 780	42039.5	3923.0	1141.0	.	26.00	94.00
WAY- 781	41928.0	3766.0	743.0	.	0.00	58.00
WAY- 782	41934.5	3771.0	899.0	18.00	15.00	84.00
WAY- 783	41929.0	3772.0	665.0	.	0.00	119.00
WAY- 785	41976.0	3784.0	872.0	24.00	18.00	140.00
WAY- 786	41942.0	3764.0	1092.0	.	41.00	13.00
WAY- 787	42038.0	3865.0	1088.0	1026.00	633.00	622.00
WAY- 789	41972.0	3820.0	1304.0	51.00	0.00	146.00
WAY- 790	42055.5	3825.5	1030.0	.	75.00	346.00
WAY- 793	42071.5	3786.0	1279.0	.	5.00	275.00
WAY- 800	41952.0	3773.5	1094.0	21.00	15.00	119.00
WAY- 801	42021.0	3867.0	1137.0	45.00	36.00	94.00
WAY- 802	42066.0	3852.5	735.0	.	0.00	66.00
WAY- 803	41949.5	3800.5	958.0	119.00	30.00	112.00
WAY- 805	42235.0	3859.5	1078.0	.	0.00	52.00
WAY- 806	42227.0	3865.0	955.0	.	0.00	47.00
WAY- 807	42196.0	3889.5	1093.0	71.00	54.00	103.00
WAY- 808	42229.5	3845.0	974.0	.	0.00	58.00

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Figure 26. (pages 73-75) Relationship of Devonian gas shale production to photolineaments in Wayne County, West Virginia. The base map is identical to figure 19. The overlays are produced from the data of table 1 and show symbolically the magnitude of natural and stimulated open flows.

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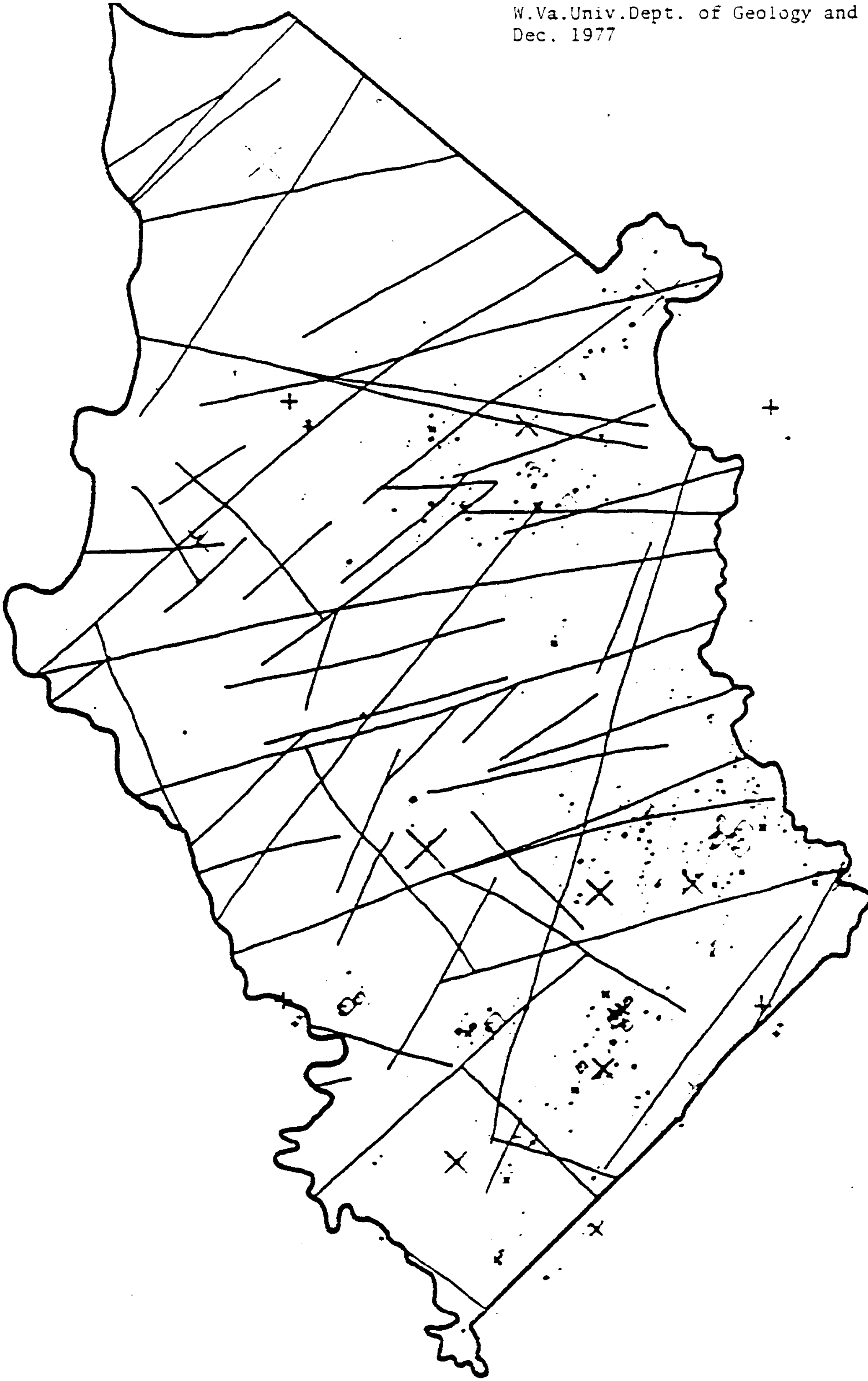

NATURAL OPEN FLOWS FOR WAYNE COUNTY

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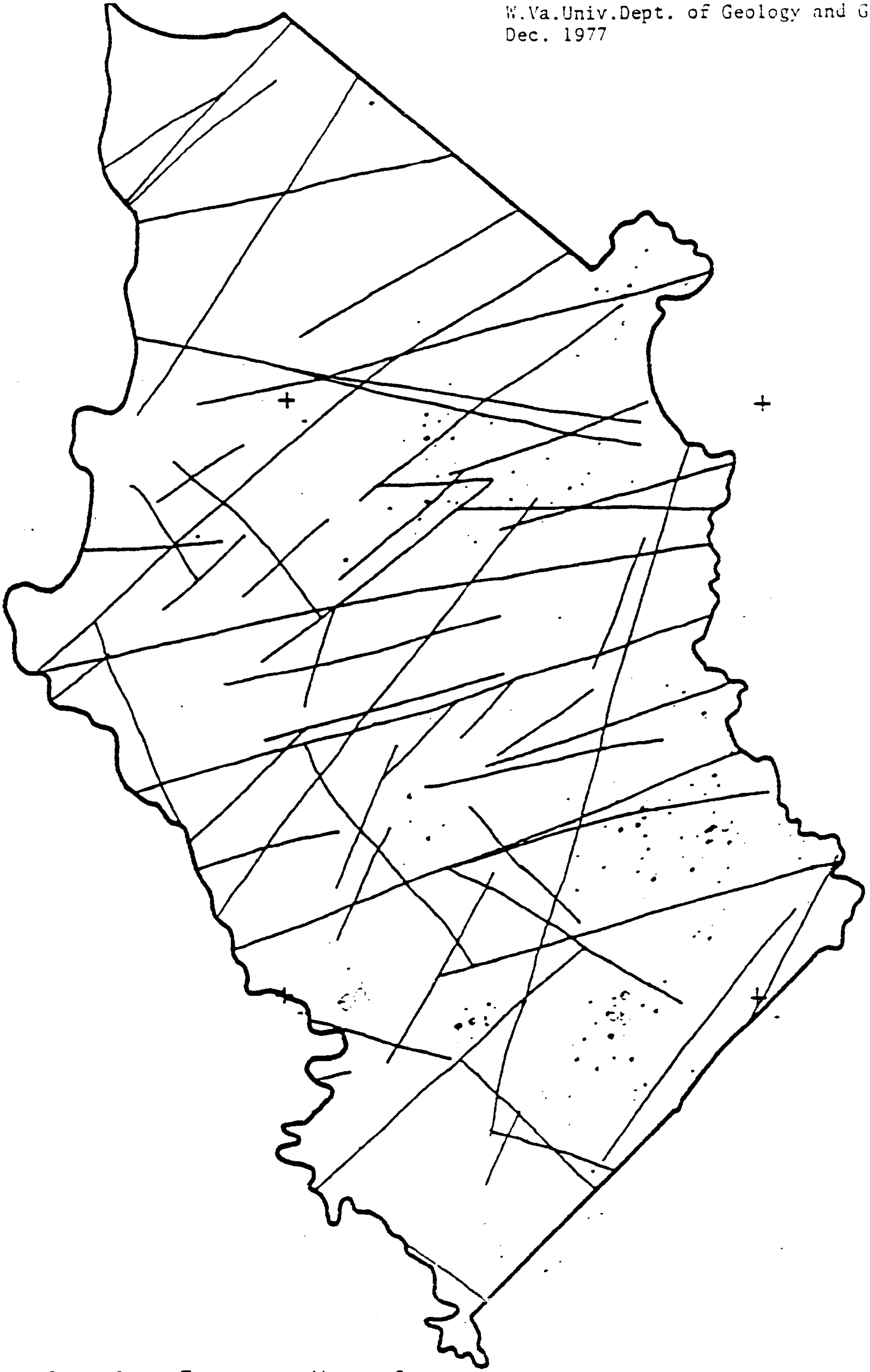

After Shot Open Flows for Wayne County

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Table 2. (pages 77-79) Devonian shale gas production for Jackson and Mason counties, West Virginia. All logs on deposit with the West Virginia Geological and Economic Survey were used for this table. See table 1 for key to labels.

DATA FOR GAS WELLS IN JACKSON COUNTY

WELL_NO	N_COORD	E_COORD	ELEV	GAS	NATURAL	AFT_SHOT
JAC- 15	.	.	585.0	50.00	10.00	20.00
JAC- 24	42789.0	4521.5	983.1	0.00	0.00	0.00
JAC- 42	42876.5	4330.5	810.0	0.00	0.00	.
JAC- 47	42978.5	4428.0	800.3	103.00	.	.
JAC- 69	42732.0	4437.0	905.0	0.00	0.00	.
JAC- 88	42702.5	4436.0	745.6	0.00	0.00	.
JAC- 93	42710.5	4422.0	910.3	0.00	0.00	.
JAC- 100	42639.5	4398.0	948.4	0.00	0.00	.
JAC- 103	43104.5	4490.0	669.7	0.00	0.00	0.00
JAC- 104	42733.5	4451.5	906.9	0.00	0.00	.
JAC- 111	42958.0	4433.0	802.5	0.00	0.00	.
JAC- 113	42727.0	4414.0	938.5	0.00	0.00	.
JAC- 137	42795.0	4400.0	972.0	0.00	0.00	0.00
JAC- 147	42704.0	4469.5	714.4	0.00	0.00	.
JAC- 161	42938.0	4421.0	653.9	133.00	.	.
JAC- 223	42978.5	4465.5	641.0	23.64	.	.
JAC- 281	42897.5	4465.5	766.2	300.00	.	.
JAC- 294	42782.0	4470.0	995.0	0.00	0.00	0.00
JAC- 297	42757.5	4392.0	881.7	0.00	0.00	.
JAC- 483	42900.5	4374.5	884.3	47.00	.	.
JAC- 555	42854.5	4376.5	685.5	.	.	211.00
JAC- 558	42928.5	4392.5	906.0	39.00	.	.
JAC- 564	43004.0	4373.5	667.0	14.00	.	.
JAC- 566	42859.5	4385.0	964.6	26.00	.	.
JAC- 568	42991.5	4399.5	891.0	50.00	.	.
JAC- 586	42993.0	4242.5	689.9	14.90	445.00	.
JAC- 596	43077.0	4381.0	588.0	0.00	0.00	0.00
JAC- 597	43016.5	4237.5	702.1	0.00	0.00	0.00
JAC- 609	42915.0	4297.5	.	.	.	.
JAC- 613	43020.5	4258.0	643.9	51.63	.	133.00
JAC- 621	43004.0	4244.5	706.6	.	.	133.00
JAC- 654	42997.0	4250.0	968.0	.	.	1309.00
JAC- 657	43017.5	4273.5	709.0	.	.	734.00
JAC- 676	43028.5	4283.5	587.0	.	.	539.00
JAC- 682	43016.0	4266.5	810.0	.	.	852.00
JAC- 687	43026.0	4299.0	564.0	.	.	582.00
JAC- 691	43016.0	4265.0	800.0	.	.	231.00
JAC- 693	43009.5	4274.0	769.0	.	.	381.00
JAC- 694	43011.5	4276.0	720.1	52.00	36.00	1852.00
JAC- 696	43018.0	4266.5	795.6	.	28.00	582.00
JAC- 697	43023.0	4279.5	586.0	.	.	560.00
JAC- 698	43009.5	4256.0	847.0	.	.	822.00
JAC- 699	43008.5	4298.5	590.0	.	.	152.00
JAC- 700	42981.0	4261.5	637.0	179.00	200.00	179.00
JAC- 701	42980.0	4252.5	657.0	.	14.50	696.00
JAC- 702	43020.0	4289.0	593.6	.	.	460.00
JAC- 703	43011.5	4285.5	607.0	.	.	582.00
JAC- 704	43022.0	4293.0	655.0	.	.	348.00
JAC- 705	43003.0	4271.0	632.0	.	.	900.00
JAC- 706	43000.0	4277.0	613.0	.	.	1981.00
JAC- 707	.	.	630.0	14.50	50.00	.
JAC- 709	43024.0	4283.5	598.0	.	.	381.00
JAC- 713	43004.5	4249.5	705.0	295.00	.	785.00
JAC- 715	43013.5	4264.0	858.0	.	.	267.00
JAC- 716	43021.5	4278.5	629.0	.	.	283.00
JAC- 717	43003.0	4265.0	611.0	.	.	1100.00
JAC- 718	43044.5	4279.0	660.0	0.00	0.00	0.00
JAC- 721	43043.0	4298.5	713.0	.	.	412.00
JAC- 722	43007.5	4283.5	609.0	23.56	73.00	528.00
JAC- 724	43018.0	4293.5	700.0	.	.	582.00
JAC- 727	42970.0	4301.0	890.6	.	.	140.00
JAC- 728	43025.0	4271.0	694.0	.	.	959.00
JAC- 731	42986.5	4268.5	665.9	10.00	5.00	762.00
JAC- 732	43014.0	4292.0	690.0	.	.	539.00
JAC- 733	43014.0	4275.5	641.0	.	.	198.00
JAC- 735	42987.0	4260.0	823.0	.	.	.
JAC- 742	43003.0	4263.0	651.0	.	.	337.00
JAC- 743	43017.5	4289.5	625.0	.	.	823.00
JAC- 746	42998.0	4263.0	880.0	.	.	823.00
JAC- 747	43029.0	4298.0	746.0	.	.	728.00
JAC- 748	43020.5	4284.0	595.0	.	.	348.00
JAC- 750	43027.5	4287.0	702.0	.	.	365.00

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DATA FOR GAS WELLS IN JACKSON COUNTY

WELL_NO	N_COORD	E_COORD	ELEV	GAS	NATURAL	AFT_SHOT
JAC- 757	43012.5	4280.5	618.8	.	.	660.00
JAC- 759	42976.5	4266.0	658.2	.	.	63.00
JAC- 760	42998.0	4274.5	725.0	15.00	15.00	146.00
JAC- 761	42989.0	4275.0	678.4	.	47.00	152.00
JAC- 762	43006.5	4281.0	610.0	.	.	539.00
JAC- 763	42992.5	4259.0	711.5	3110.00	3110.00	.
JAC- 764	42993.5	4265.0	643.7	33.00	.	413.00
JAC- 765	42989.5	4287.0	641.5	4.00	4.00	246.00
JAC- 766	42997.5	4286.5	692.7	0.00	0.00	6.45
JAC- 767	42981.5	4272.5	743.0	0.00	0.00	4.00
JAC- 768	43003.5	4283.5	650.7	.	4.00	38.00
JAC- 769	43016.0	4285.5	578.0	.	.	1300.00
JAC- 774	43019.0	4262.5	794.0	.	.	321.00
JAC- 775	42994.0	4271.0	632.0	.	.	203.00
JAC- 776	42982.5	4265.5	656.0	.	.	184.00
JAC- 778	42984.0	4248.5	826.0	.	.	3480.00
JAC- 779	43024.0	4294.5	571.0	.	.	377.00
JAC- 780	42980.0	4258.5	786.0	.	.	179.00
JAC- 783	43002.0	4255.0	841.0	.	.	376.00
JAC- 784	43018.0	4297.0	761.0	0.00	0.00	0.00
JAC- 787	42975.5	4246.5	605.0	.	.	730.00
JAC- 789	42973.5	4299.0	743.9	18.00	15.00	84.00
JAC- 790	42974.5	4304.0	756.9	.	6.00	55.00
JAC- 792	43029.5	4273.0	.	.	.	622.00
JAC- 793	43034.5	4301.5	669.0	.	.	337.00
JAC- 800	43035.5	4285.0	663.0	.	.	207.00
JAC- 802	43059.5	4503.5	630.0	.	.	0.00
JAC- 804	43063.5	4503.0	814.0	.	.	0.00
JAC- 835	42880.5	4535.5	916.0	.	.	0.00
JAC- 847	42924.0	4382.0	913.0	.	.	152.00
JAC- 852	.	.	979.0	.	.	0.00
JAC- 864	.	.	890.0	.	.	360.00
JAC- 891	42918.5	4376.0	.	.	.	471.00
JAC- 935	43002.0	4267.0	.	0.00	0.00	0.00
JAC- 945	.	.	746.0	.	.	53.00
JAC- 990	42833.5	4356.0	939.1	.	.	32.00
JAC-1002	42853.0	4450.0	778.7	.	.	84.00
JAC-1006	42840.0	4351.0	851.9	41.00	.	.
JAC-1012	42852.0	4350.5	1033.6	28.00	.	.
JAC-1037	42848.0	4359.0	1009.2	28.00	.	.
JAC-1070	42955.5	4387.5	601.3	23.00	.	.
JAC-1075	42954.0	4389.5	602.9	14.00	.	.
JAC-1077	42960.0	4379.0	843.0	60.00	.	.
JAC-1088	42958.0	4407.5	924.0	14.00	.	.
JAC-1105	42953.5	4373.5	908.5	.	.	.
JAC-1124	42965.5	4417.0	805.9	27.90	.	.
JAC-1141	42919.0	4340.0	856.4	.	.	.
JAC-1154	42932.5	4361.0	662.4	.	.	.
JAC-1202	43003.5	4276.5	734.5	.	33.30	100.00
JAC-1209	42985.5	4372.5	712.0	0.00	0.00	0.00
JAC-1233	43003.5	4274.0	625.0	14.90	.	.
JAC-1294	.	.	748.9	.	.	25.00
JAC-1295	.	.	801.0	0.00	0.00	0.00
JAC-1299	43023.0	4313.0	.	.	.	.
JAC-1358	42850.5	4411.0	743.6	.	.	133.00
JAC-1363	42844.0	4408.5	929.2	.	.	133.00
JAC-1364	42850.5	4417.0	842.2	.	.	84.00
JAC-1365	42994.5	4255.0	833.0	.	.	273.00
JAC-1369	42979.5	4241.5	835.0	.	.	1007.00
JAC-1371	43030.5	4264.5	662.0	.	0.00	111.00
JAC-1373	42989.0	4239.5	870.0	.	0.00	298.00

DATA FOR GAS WELLS IN MASON COUNTY

WELL_NO	N_COORD	E_COORD	ELEV	GAS	NATURAL	AFT_SHUT
MAS- 3	42995.5	4220.0	634.0	.	.	350.00
MAS- 22	.	.	620.8	0.00	0.00	0.00
MAS- 26	.	.	601.0	0.00	0.00	0.00
MAS- 38	42990.0	4232.5	671.3	60.00	.	103.00
MAS- 39	42978.5	4224.0	710.2	179.00	84.00	.
MAS- 40	42995.5	4230.5	616.0	.	.	39.00
MAS- 41	43009.5	4184.5	677.7	0.00	0.00	0.00
MAS- 42	42992.5	4208.5	883.0	119.00	.	29.00
MAS- 44	43004.0	4224.5	842.5	50.00	.	21.00
MAS- 45	43006.5	4211.5	876.3	0.00	0.00	0.00
MAS- 46	42976.0	4205.0	957.7	0.00	0.00	0.00
MAS- 47	42966.5	4230.0	920.2	42.00	.	60.00
MAS- 48	42962.0	4218.5	814.5	0.00	0.00	0.00
MAS- 51	42970.0	4245.0	1019.0	.	.	666.00
MAS- 52	42951.0	4252.5	843.0	.	0.00	18.00
MAS- 53	42960.5	4251.0	795.0	.	.	25.00
MAS- 54	42962.5	4241.5	660.0	0.00	0.00	0.00
MAS- 58	42806.0	4229.5	725.5	.	.	14.00
MAS- 62	42832.0	4251.5	623.4	0.00	0.00	0.00
MAS- 64	.	.	834.0	0.00	0.00	0.00
MAS- 65	.	.	556.6	0.00	0.00	0.00
MAS- 66	.	.	680.2	0.00	0.00	0.00
MAS- 104	.	.	652.0	.	.	11.00
MAS- 133	.	.	643.0	.	.	50.00
MAS- 134	42972.5	4241.5	921.0	.	0.00	158.00
MAS- 138	42976.0	4235.5	.	.	0.00	72.00

Figure 27. (pages 81-83) Relationship of Devonian shale gas production to photolineaments in Jackson and Mason counties, West Virginia. Base map is identical to figure 20. Overlays show the magnitude of values of open flows. Size of symbols in this figure relative to figure 26 is one-half.

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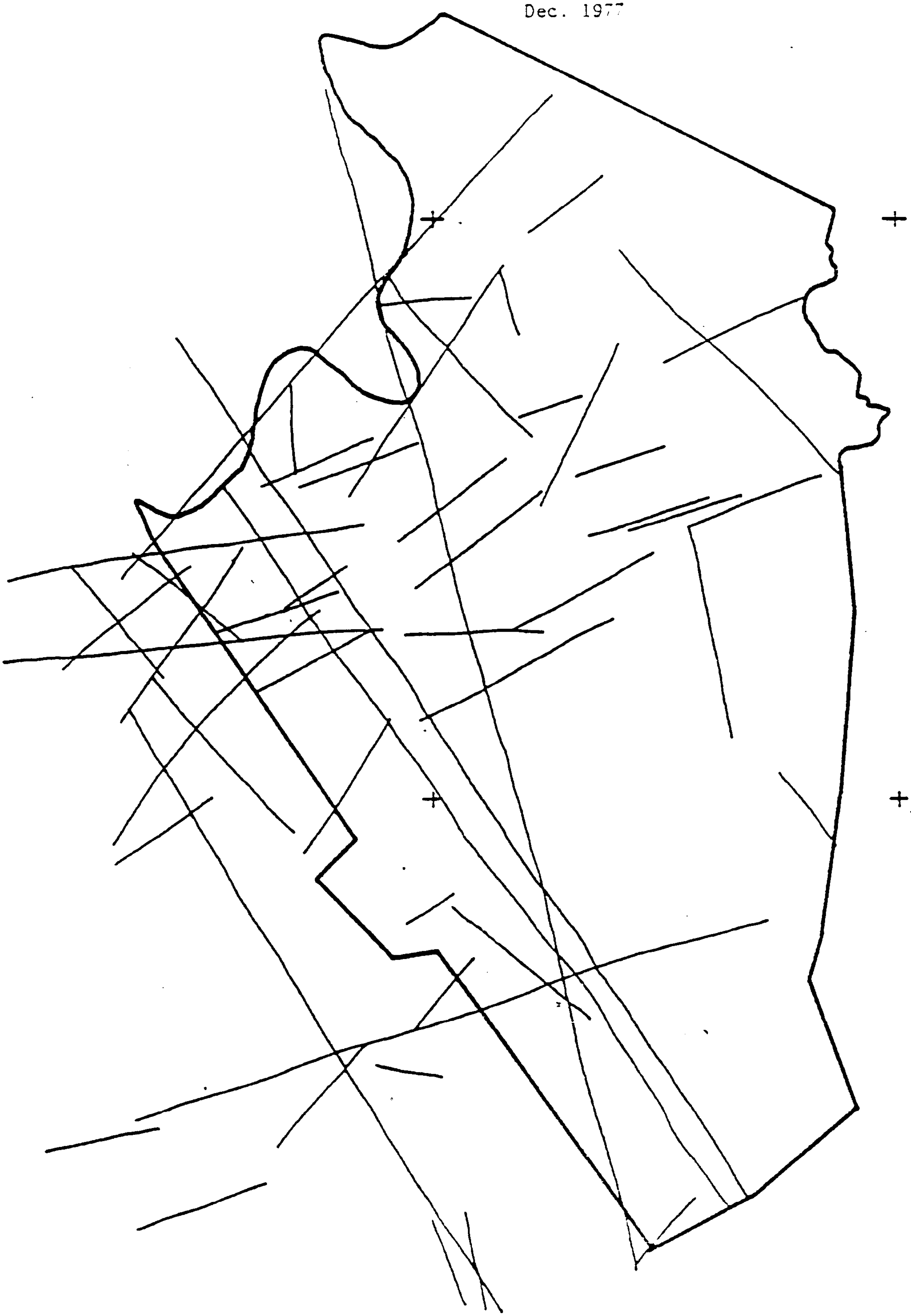

NATURAL OPEN FLOWS FOR JACKSON & MASON COUNTIES

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AFTER SHOT OPEN FLOWS FOR JACKSON & MASON COUNTIES

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flows do fall on or near the photolineaments, even more fall between them. There are no high natural open flows on or near photolineaments (except possibly for one case).

The picture for the Jackson-Mason County area is similar. An additional photolineament map was produced from imagery at a scale of 1:65,000 for the Cottageville Gas Field because of the close spacing and generally higher yields of those wells. The results were no different than those above. The wells with high initial open flows were not near photolineaments.

These results are not entirely unexpected in light of the probable characteristics of the features represented by photolineaments. Such features are generally zones of undetermined (but ranging at least from 40 feet to 1 mile) width in which the rocks differ from those around them, and in particular, where the rocks are more fractured than the surrounding rock. If no secondary mineralization has caused sealing of the fractures, such zones should be much more permeable than the country rock. However, since photolineaments, by the fact that they can be seen on aerial imagery, must represent conditions at the surface of the earth, and if these conditions (i.e., fracturing) exist to the depth of the gas reservoir, then it is entirely reasonable that the gas has been vented to the surface through the fracture permeability. The only conditions under which one might expect better production due to such fracture zones would be if they were very well sealed above the gas reservoir.

Thus, it appears that the locations of photolineaments are poor choices for gas wells in the area investigated. Several possible explanations exist for the apparent discrepancy of findings of this study and that referenced for the Haysi Field (Ryan, 1976). First, the lithologies of the producing formations are different. The producing horizon in the Haysi Field is the Berea siltstone; the producing horizon in western West Virginia is the Devonian shale. The two rock types behave differently under stresses which produce fracturing. Second, the Haysi Field is located in an area of Appalachian thin-skinned tectonics, where the areas of this study are probably not. Another point to be considered which may have a bearing on this relationship is one indicated by Kulander, Dean, and Barton (1977). They investigated fractures in a core from near Hazard, Kentucky, which, although outside of the area considered directly here, is in a somewhat similar tectonic regime. In the Hazard well, it was found that most of the natural fractures of the core were horizontal. This, of course, is the expected situation since it is not very likely that many vertical fractures would be intersected by a vertical 6-inch diameter hole. Nevertheless, if the gas conduits in the Devonian shales (which are relatively incompetent rocks) were primarily horizontal fractures and those in the more competent sills and sands of the Berea (say) were at least partly vertical fractures, such a difference in the relationship between photolineaments and production as is seen might be reasonable.

Also, considering the same point, if horizontal fractures are the primary natural conduits of gas to wells, and if the photolineaments shown on figures 26 and 27 were the main vertical fracture zones, then the vertical fractures may have vented sufficient gas to make the immediate vicinity non-productive. At some distance from the vertical fracture zones, a well intersecting the horizontal fracture would have a better chance of producing. Artifical stimulation would disrupt the natural relationship, and thus could give the relationship shown for photolineaments and stimulated production.

Further analysis of the data may show another relationship of interest. If the geological disturbance that created the vertical fracture zone also opened further or increased the frequency of horizontal fractures (along the lines of the domain boundary concept of Kowalik and Gold, 1976), then the two opposite controls on gasyield --venting through vertical fractures and decreased permeability away from the lineaments--may show a complex relationship wherein highest gas yield may occur at some optimum distance from a photolineament. Such an analysis is now in progress.

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Chapter 4 DATA ANALYSIS

Section 1 Statistical Techniques

A rather common problem for geologists is the analysis of data consisting of sets of orientation measurements. These data may consist of measurements of paleocurrent direction, joint or bedding strike, stream alignments, or other linear features. Such data present certain problems to the analyst because such data are distributed around a circle rather than stretched out along a line. As a result there is no reference origin nor is there an absolute "greater than" or "less than" relationship between any two values. The problem of the analysis of orientation data has occupied scientists in many fields and the body of literature resulting from the work is quite large. Mardia (1972) presents a summary of many of the techniques which have been developed.

Most attention so far has been given to data sets which can often be handled by the use of parametric statistics (for example, see Jones, 1968; Rao and Sengupta, 1972). Generally speaking, such data sets are large and, for most techniques, should be unimodal and fit a circular normal distribution (or it must be possible to subdivide such data sets into ones which satisfy these requirements). Usually these techniques are fairly cumbersome for routine use, particularly in the field since they require at the least a calculator and a considerable amount of time. Nonparametric techniques, on the other hand, are usually quite simple to apply, and also lend themselves to data which do not satisfy the requirements for parametric tests. Such tests as the Chi-square and Kolmogorov-Smirnov are in common use; however, they are often applied to orientation data without a clear understanding of the test's characteristics and, therefore, sometimes incorrectly.

The techniques described by Siegel (1956) were investigated for applicability to the type of data acquired in this project. The data under consideration here consists of sets of joint strike readings from single outcrops and photolineament directions taken from imagery. Comparisons are to be made between pairs of data sets to determine if they are alike in orientation patterns (technically, whether the distributions can be said to be from the same populations). The data sets are multimodal and cannot be separated into subsets which fulfill the requirements of parametric tests. Other types of data such as paleocurrent data, stratigraphic strikes within reasonably small areas, and petrofabric data often can be made to fulfill those requirements and the tests here discussed are not needed by those working with such data, although thev may be useful nevertheless.

Of the tests described by Siegel (1956), only two--the Wald-Wolfowitz runs test and the Kolmogorov-Smirnov test as modified by Kuiper (1960)--were found satisfactory for testing whole data sets or orientation measurements, and all comparisons made and reported here were done using these two techniques. A third test--the Chi-Square--was found to be of marginal value under some special circumstances but was not generally used.

Section 2 Graphical Techniques

The display of geological data which includes compass direction as a measurement has always presented some problems. Traditionally, most such data has been presented in one of four forms--polar or cartesian histograms or polygons. Each form has certain advantages and disadvantages. However, except for the brief discussion by Gay (1976), little has been said about the properties of various types of orientation plots. Since visual analyses of directional data are frequently made from graphical representations of such data, there is a need to investigate the variations introduced into the plots by the various methods employed to draw them. Without an understanding of the effects of plotting methods on the appearance of the resulting plots, erroneous conclusions may be reached when visual interpretation methods are employed with these plots.

Regardless of the form chosen for the plot of orientation data, values need to be chosen for two plotting parameters, the stepping increment and the averaging window. The stepping increment is that interval which separates the points to be plotted. The averaging window is that interval which is considered for any given plotting point. Values of the two parameters may be equal, but the averaging window cannot be less than the stepping increment or information will be lost. Note that if the stepping increment and the averaging window are equal, the normal raw data plot will be produced. If the window is greater than the increment, a smoothed plot will be produced There is no other requirement for the relationship between these two values. However, computation is easier if the window is an odd integral multiple of the increment.

The choice of values for the two plotting parameters can be quite important. In particular, the values need to be chosen in terms of the smallest peak separation that it is desired to show. If the stepping increment equals or exceeds one-half of this separation, adjacent peaks will merge. The averaging window's size also controls how the peaks will appear. The larger the window, the more adjacent peaks will merge. In general, two adjacent peaks will merge if the averaging window is greater than the peak separation. However, this is also dependent on the character of the peaks themselves. Two fairly broad peaks will merge with smaller windows than will two fairly sharp peaks.

A second factor to consider is how much detail it is desired to show. If the shape of the peaks is to be shown, both the increment and window size should be kept small. The increment must be a fairly small fraction of the peak width. The window size is not quite as critical, but it should not exceed the peak width.

An additional important consideration is required if different data sets are to be compared. Since different values of the plotting parameters clearly produce plots of different appearance, it is important that the values be the same for plots which are to be visually compared to each other.

Once the values have been chosen for the increment and the window, it is important that the plots be constructed so that comparisons between them can be made. Since the number of data used for different plots may differ, some adjustment should be made to make the plots of comparable size. The following procedure is one method of assuring comparability.

First, the data must be distributed among the plotting increments so that the value plotted at each increment corresponds to the data items within the window centered on that increment. This value would be either simply the count of data items or the cumulative lengths for data where length measurements are made. At this point (see table 3 for symbol explanation):

$$\sum_{i=1}^{n} K_i = N*I$$

In order to assure comparable plots,

$$\Sigma K_i = 1$$

should be true. Thus each K_i should be divided by $N * I$. However, because the plotting process automatically multiplies K_i by S, in is necessary to divide each K_i by $N * W$. This assures that plots of different data sets will all have the same area under the plot curve. If it is desired to have the areas that are included within circular plots be visually comparable, the

Table 3 Symbols used in equations

i - counter

I - number of increments per window ($I = W/S$)

K_i - value in the ith increment

n - number of increments for entire plot

N - total number of data items (or sum of lengths) in data set

S - size of the increment step

W - width of the averaging window

square root of each value must be taken. The data may now be plotted in whatever form the user prefers. Multiplication of each K_i by 100 cm or 50 inches will normally result in a plot of reasonable size and proportions.

Section 3 Computer Programs

A computer program which plots orientations diagrams as discussed in the previous section and performs the statistical comparisons discussed in section 1 of this chapter has been produced and is on file with the Morgantown Energy Research Center (MERC). This program produced the rose diagrams of figures 16-18.

A program to produce the maps such as used for plates 1-9 and the overlays for figures 26 and 27 is also on file with MERC. The program is designed to use rectangluar grid coordinates as input and will plot well production data in numeric or symbolic form, fracture orientation data as either preferred orientations or complete rose diagrams, and lineaments and single points either labelled or unlabelled.

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